Food and Agriculture Organization of the United Nations

# The role of livestock in circular bioeconomy systems

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Food and Agriculture Organization of the United Nations
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# Foreword

These guidelines have been produced by the Food and Agriculture Organization of the United Nations (FAO) Livestock Environmental Assessment and Performance (LEAP) Partnership, a multistakeholder initiative which aims to improve the environmental sustainability of livestock supply chains through better methods, metrics and data.

As global populations grow and food demand increases, adopting a circular bioeconomy is essential to reduce resource use, improve efficiency, and make better use of biomass and energy, including through the reuse and recycling of by-products. Livestock play a fundamental role in this process by converting non-edible biomass into high-value animal-sourced foods, organic fertilizers and renewable energy. This reduces food–feed competition, enhances soil health, mitigates greenhouse gas emissions and closes nutrient cycles, thereby making agricultural and biological systems more sustainable and improving global food security. The use of animal by-products also supports bio-based industries, including pharmaceuticals, nutraceuticals, cosmetics and bioenergy.

The lack of a comprehensive database and standardized methodologies has been a major barrier when it comes to assessing the extent to which the livestock sector contributes to the circular bioeconomy. This guideline helps close this gap, resulting in a clearer understanding, transparent use and communication of metrics, and driving tangible, measurable improvements in environmental performance.

The guideline is designed for a broad audience, including livestock producers, supply chain partners, farming organizations, processors and retailers who are looking to explore the synergies, trade-offs and interactions of livestock within a circular bioeconomy framework. It is also relevant to non-livestock stakeholders by offering insights into how they can engage with the sector through recycling and upcycling residues and waste. Moreover, the guideline is a valuable resource for policymakers with an interest in circular bioeconomy strategies for livestock supply chains.

The guideline has been developed by a dedicated Technical Advisory Group (TAG) of experts in the fields of livestock production systems, nutrition and circular production systems, who represent various geographical regions and interest groups. As Chair of the FAO LEAP, I would like to thank the TAG Chairs and the expert group for their time and expertise. During the development process, the draft guideline was submitted for both technical and public review to improve the quality of the recommendations it makes and ensure that the technical document meets the needs of those aiming to improve environmental performance through a robust assessment practice.

Since it was established in 2012, the LEAP Partnership has published a wide range of guidelines and technical reports with contributions from more than 450 experts across the world. This has improved the global, regional and local understanding of how livestock and livestock production systems interact with the environment. The resulting knowledge has led to actions designed to improve environmental sustainability, while making the livestock sector more economically and socially viable.

In the next phase of LEAP, our focus will remain on expanding the global reach of the guidelines and making them accessible to more countries and farmers, eventually bringing about change on the ground. Central to this effort is the continued strengthening of existing partnerships while building new ones with FAO Member Countries and global partners. This also involves collaborating with other multilateral programmes to share information and resources for the benefit of all. We now also have new tools at our disposal to support outreach, including the LEAP Navigator AI tool and the FAO e-learning courses.

The LEAP Partnership is founded on a voluntary and collaborative process involving FAO and three main stakeholder groups: the private sector, FAO Member Countries and non-governmental organizations. I would like to thank members of the LEAP Steering Committee for their efforts in ensuring that LEAP remains at the forefront of change, guided by the principles of equity and balanced representation. I also wish to acknowledge a growing number of partners for contributing to the Partnership's success. Special thanks go to Thanawat Tiensin, Assistant Director-General and Director of the Animal

Production and Health Division at FAO. Finally, I extend my deep appreciation to the LEAP Secretariat whose outstanding work has been essential in the progress we have made and will continue to build on in the years ahead.

**Peter Ettema**
FAO LEAP Chair 2024

# FAO Livestock Environmental Assessment and Performance (LEAP) Partnership

The FAO Livestock Environmental Assessment and Performance (LEAP) Partnership, established in 2012, is a multi-stakeholder initiative dedicated to enhancing the environmental performance of livestock systems while ensuring their economic and social sustainability. The FAO LEAP Partnership develops science-based environmental assessment methodologies aligned with international standards to support evidence-based policy and action. The LEAP technical guidelines, formulated by Technical Advisory Groups (TAGs), undergo rigorous internal, technical and public reviews to guarantee reliability and relevance. By engaging end users throughout the process, FAO LEAP ensures its tools are applicable across diverse scales and geographical contexts. FAO LEAP aims to equip stakeholders with the tools and insights needed to drive positive change in the livestock sector through evidence-based policies and business strategies. It fosters science-based collaboration among governments, the private sector, academia, NGOs and civil society organizations.

### FAO LEAP PARTNERSHIP STEERING COMMITTEE

The Steering Committee of the FAO LEAP Partnership provides overall leadership and approves the work programme of the Partnership. It comprises representatives from three key stakeholder groups: 1. governments: Australia, Brazil, Canada, Costa Rica, France, Ireland, Kenya, Kingdom of the Netherlands, New Zealand, Switzerland and Uruguay; 2. NGOs and civil society organizations: Compassion in World Farming, Environmental Defense Fund, International Union for Conservation of Nature, World Alliance of Mobile Indigenous Peoples, and World Wildlife Fund; 3. the private sector: International Dairy Federation, International Egg Commission, International Feed Industry Federation, International Meat Secretariat, International Poultry Council and World Renderers Organization.

### FAO LEAP PARTNERSHIP SECRETARIAT

The FAO LEAP Secretariat, hosted by the FAO Animal Production and Health Division, ensures that LEAP activities follow international best practices. As the Partnership's central coordinating body, the Secretariat offers technical and administrative support to FAO LEAP partners and participants. It also supports Technical Advisory Groups (TAGs) in developing guidelines and ensures they align with both FAO and the Partnership objectives. The FAO LEAP Secretariat includes Xiangyu Song, FAO LEAP Secretariat Manager; Paolo Medei, Sustainable Agriculture Specialist; Edoardo de Santis, Multistakeholder Partnerships Specialist; Julie Hanot, Partnership Intern; and Maud Lebeaupin, Partnership Intern.

### ACKNOWLEDGEMENTS

This publication is produced by the FAO LEAP Partnership. The Partnership acknowledges the contributions of all FAO LEAP partners and participants. The Partnership also acknowledges both the TAG for developing these guidelines and the LEAP Steering Committee for providing overall guidance. The FAO LEAP Partnership recognizes the leadership of its Chairs: Hsin Huang, International Meat Secretariat (2022); Julie Adamchick, World Wildlife Foundation (since January 2023); Pablo Manzano Baena, International Union for Conservation of Nature (since June 2023); Peter Ettema, Ministry for Primary Industries New Zealand (2024); and FAO LEAP co-Chair Thanawat Tiensin, Assistant Director-General, Director of the Animal Production and Health Division (NSA) and Chief Veterinarian, FAO.

# Collaborators

This publication is a product of the FAO LEAP Partnership.

## CIRCULAR BIOECONOMY APPROACHES TECHNICAL ADVISORY GROUP

The TAG on circular bioeconomy approaches (CBA) conducted the research and developed the technical content of the guidelines. The CBA TAG was established in February 2023 and composed of 3 TAG Leaders and 33 TAG Members (listed in alphabetical order by surname).

### TAG Leaders

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- **Tim McAllister** (Agriculture and Agri-Food Canada, Canada)

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## TECHNICAL SUPPORT

Technical support was provided by Xiangyu Song, FAO LEAP Secretariat Manager; Paolo Medei, Sustainable Agriculture Specialist; Edoardo de Santis, Multistakeholder Partnerships Specialist; Dominik Wisser, Livestock Policy Officer; Aimable Uwizeye, Livestock Policy Officer; Julie Hanot, Partnership Intern; Maud Lebeaupin, Partnership Intern; Sara Giuliani, Communications Specialist; Claudia Ciarlantini, Information Management Officer; Monica Rulli, Livestock and Climate Change Specialist. Professional editing and proofreading were done by Agnieszka Gratza. The graphics were designed by Francesco De Lorenzo.

# Multistep review process

This publication underwent multistep review processes: internal (February 2024), technical (March and April 2024), the FAO Animal Production and Health Editorial Committee review (April 2024) and public reviews (August and September 2024).

### Step 1: Internal review

The FAO LEAP Secretariat and the FAO LEAP Partnership Steering Committee members reviewed the initial draft provided by the CBA TAG ahead of the peer review.

### Step 2: Technical review

The following technical reviewers and organizations contributed to peer reviewing this report (listed in alphabetical order by surname):

- **Alan Duncan** (University of Edinburgh, United Kingdom)
- **Daniel Puente Rodríguez** (Wageningen University & Research, Kingdom of the Netherlands)
- **David Styles** (University of Galway, Ireland)
- **Jiaqi Wang** (Chinese Academy of Agricultural Sciences, China)

### Step 3: FAO Animal Production and Health Editorial Committee review

The document was reviewed by members of the FAO Animal Production and Health Editorial Committee.

### Step 4: Public review

The following scientists and organizations contributed to the public review of this report (listed in alphabetical order by surname):

- **Jan Amanullah** (University of Agriculture Peshawar, Pakistan)
- **Kara Barnes** (Canadian Roundtable for Sustainable Beef, Canada)
- **Flavia Casu** (FAO, Italy)
- **Lucas Cypriano** (World Renderers Organization, Brazil)
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- **Agriculture and Agri-Food Canada**, Canada
- **Cargill**, United States of America
- **European Sustainable Phosphorus Platform**, Belgium

The Public Review version is available on the FAO LEAP website at the following link:
https://openknowledge.fao.org/handle/20.500.14283/cd1948en

## PERIOD OF VALIDITY

These guidelines are to be periodically reviewed to ensure the information and methodologies on which they rely are valid. At the time of development, no mechanism is in place to ensure this. To obtain the latest version, the user is invited to visit the FAO LEAP website (www.fao.org/partnerships/leap).

# Abbreviations

| | |
|---|---|
| **ABP** | animal-based product |
| **AcoD** | anaerobic co-digestion |
| **AD** | anaerobic digestion |
| **ALCA** | attributional life cycle assessment |
| **ANF** | antinutritional factor |
| **ASF** | animal-sourced food |
| **BOD** | biological oxygen demand |
| **BSF** | black soldier fly |
| **CBA** | circular bioeconomy approaches |
| **CiFoS** | circular food system |
| **COD** | chemical oxygen demand |
| **CP** | crude protein |
| **DM** | dry matter |
| **FM** | fishmeal |
| **FO** | fish oil |
| **FAO** | Food and Agriculture Organization of the United Nations |
| **GHG** | greenhouse gas |
| **IK** | Indigenous knowledge |
| **ISO** | International Organization for Standardization |
| **LCA** | life cycle assessment |
| **LCB** | low opportunity cost by-product |
| **LEAP** | Livestock Environmental Assessment and Performance |
| **LUC** | land-use change |
| **NDF** | neutral detergent fibre |
| **NOx** | nitrogen oxides |

**NUE** nutrient use efficiency

**OLR** organic loading rate

**PBs** planetary boundaries

**PBP** plant-based product

**PCBs** polychlorinated biphenyls

**PPB** phototrophic purple bacteria

**PSMs** plant secondary metabolites

**RF** rendered fat

**SBM** soybean meal

**SDGs** Sustainable Development Goals

**UN** United Nations

**UNECE** United Nations Economic Commission for Europe

**WHO** World Health Organization

**WOAH** World Organisation for Animal Health

**Chemical formulae and elements**

**Ca** calcium

**$CH_4$** methane

**$CO_2e$** carbon dioxide equivalent

**Cr** chromium

**Cu** copper

**K** potassium

**Mg** magnesium

**N** nitrogen

**$NH_3$** ammonium

**$N_2O$** nitrous oxide

**P** phosphorus

**Unit of measurement**

**ktpa** kilotonnes per annum

# Glossary

**Allocation**

The partitioning of the input or output flows of a process or product system between the product system under study and one or more other product systems.

**Animal-based products (ABPs)**

All co-products from livestock production, such as meat, dairy, fibre (e.g. wool), eggs and fish from aquaculture and fisheries, as well as any other materials derived from their processing.

**Animal-sourced foods (ASFs)**

All foods derived from animals, which are broadly categorized as meat, eggs, dairy, honey and fish (including all aquatic animals).

**Biomass**

A material of biological origin, excluding material embedded in geological formations and material transformed into fossilized material as well as peat.

**Biodiversity**

The variability among living organisms from all sources, including, *inter alia*, terrestrial, marine and other aquatic systems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems [Article 2 of the Convention on Biological Diversity].

**Bioeconomy**

The production, use and conservation of biomass, including the related knowledge, science, technology and innovation, to provide information, products, processes and services.

**By-product**

A material produced during the processing (including slaughtering) of a livestock or crop product that is not the primary product of the activity (e.g. oil cakes, meals, offal or skins). Most of the by-products are considered of low economic value or at least lower than the main product (i.e. the product that drives production).

**Circular bioeconomy**

The production, use and conservation of biomass to provide products and ecosystem services across all economic sectors in the most efficient way while respecting planetary boundaries, by avoiding or preventing the use of raw materials, reducing waste, reusing and recycling of biomass. It also concerns social (fairness and accessibility) as well as animal health and well-being criteria.

**Circular economy**

A system in which waste materials are avoided as much as possible and nature is regenerated. In a circular economy, products and materials are kept in circulation through processes such as maintenance, reuse, refurbishment, remanufacture and recycling.

**Circularity**

A measure of the degree to which raw resources are not lost to the environment but present in the final product(s) or reused and reduced in processes, thereby substituting for input of "new" resources.

**Co-products**

Any of two or more products coming from the same unit process or product system.

**Crop residues**

The biomass left in an agricultural field after the crop has been harvested.

**Dead livestock**

Animals found dead on farms, or euthanized prior to slaughter from natural causes or because of natural disasters.

**Ecosystem**

A system in which the interaction between different organisms and their environment generates a cyclic interchange of materials and energy.

**Ecosystem services**
The benefits people obtain from ecosystems. These include provisioning services such as food and water, regulating services such as flood and disease control, cultural services such as spiritual and recreational benefits, and supporting services such as nutrient cycling that maintain conditions for life on Earth.

**Emission**
The release of polluting substances into the atmosphere and discharges to water and land.

**Environmental impact**
Any change to the environment, whether adverse or beneficial, wholly or partially resulting from an organization's activity, product or service.

**Feed**
Any single or multiple material, whether processed, semi-processed or raw, intended to be fed directly to animals.

**Feed ingredient**
A component or constituent part of any combination or mixture making up a feed, whether or not it has nutritional value for the animal diet, including feed additives. Feed ingredients are of plant, animal or aquatic origin, or other organic or inorganic substances.

**Food**
Any single or multiple materials, either raw or processed, intended for human consumption. It includes a wide variety of items, ranging from fruits, vegetables, grains and legumes to meat, eggs, dairy, honey and fish (encompassing all aquatic animals), as well as their derived products.

**Food system**
A complex web of activities involving the production, processing, transport and consumption of food.

**Food system modelling**
A model which describes the food system by means of a map with social, economic and ecological variables.

**Footprint**
A metric used to report life cycle assessment (LCA) results that addresses an area of interest. It represents the sum of emissions and/or discharges resulting from the production of one unit of the final product.

**Greenhouse gas (GHG)**
A gaseous constituent of the atmosphere, both natural and anthropogenic, that absorbs and emits radiation at specific wavelengths within the spectrum of infrared radiation that the Earth's surface, the atmosphere and clouds emit.

**Life cycle assessment (LCA)**
The compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system through its life cycle.

**Low opportunity cost by-product (LCB)**
A by-products used as a feed ingredient selected during the formulation process because of its lower cost.

**Manure**
A general term denoting any unprocessed organic material derived from animal excreta (faeces and urine), potentially including bedding material, feed waste and/or washing water.

**Manure management**
The collection, storage, transport and application of manure to land. It may also include treatments like composting and anaerobic digestion.

**Nutrient**
A substance required by a living organism for growth and development.

**Plant-based products (PBPs)**
All co-products from plant production, such as grains, fibres, hulls, meals and any other materials derived from the processing of the main product.

**Residual**
Any material resulting from or leaving the product system in the condition that it was in during the creation of the main product.

**Waste**
Any substance or object that the holder discards, intends to or is required to discard after primary use.

**Waste management**
The process of collecting, transporting, processing and disposing of waste in an efficient and environmentally responsible manner.

# Executive summary


Redesigning livestock systems to integrate circularity principles into livestock production is a critical step towards building a more resilient and sustainable food system. The Livestock Environmental Assessment and Performance (LEAP) Partnership of the Food and Agriculture Organization of the United Nations (FAO) produced these guidelines to offer insights into the practices and products used to strengthen circularity in the livestock sector. Aimed at all stakeholders involved in or associated with livestock production, the guidelines explore the synergies, trade-offs and interactions of livestock within a circular bioeconomy framework.

The document was developed by a dedicated Technical Advisory Group (TAG) of experts in livestock production systems, nutrition and circular production systems, representing various geographical regions and interest groups. The TAG contributed to shaping the methodology, collecting data and information, and conducting literature reviews. Prior to publication, the guideline went through an extensive public review process that included academia, extension services, countries, the private sector, NGOs, global and national initiatives associated with LEAP, and other LEAP partners.

Livestock play a key role in a circular bioeconomy by converting non-edible biomass, such as pastures and forages, agricultural residues and food industry by-products into high-value animal-sourced foods, organic fertilizers and renewable energy. In so far as it recycles nutrients and makes use of low-opportunity-cost biomass, livestock contribute to reducing food–feed competition, enhancing soil health and closing nutrient cycles. As a result, it makes agricultural systems more sustainable and strengthens global food security.

Beyond food production, livestock systems support bio-based industries by valorizing animal by-products such as hides, bones and fats into materials for pharmaceuticals, cosmetics and bioenergy. In addition, manure-based biogas production provides a renewable energy source while mitigating greenhouse gas emissions.

The guideline provides an overview of widely used metrics and indicators for assessing the environmental impact of livestock production within a circular bioeconomy, outlining the strengths and limitations of each approach. It examines the use of plant- and animal-based by-products for feed, as well as the valorization of residuals, such as manure, in circular bioeconomy systems. Regional case studies illustrate practical recovery strategies and circular bioeconomy innovations. The document also explores the political and regulatory implications of policies designed to promote the circular bioeconomy, their effectiveness and the challenges faced in supporting the use of by-products and residuals.

This document is intended for livestock producers and supply chain partners – feed producers, farming organizations, processors and retailers, among others – who aim to improve the environmental performance of their production systems. It also offers valuable insights to non-livestock stakeholders looking to collaborate with the livestock sector through the recycling and upcycling of residuals and waste. Moreover, the guidelines are a useful resource for policymakers interested in fostering circular bioeconomy strategies for livestock supply chains.

# Chapter 1
# Introduction: Circular bioeconomy systems

The circular bioeconomy offers a transformative approach to sustainability by fostering the efficient use, reuse and regeneration of renewable biomass, that is to say animals, humans, plants, microorganisms and their derived products. This provides an effective solution to global challenges such as resource depletion, waste management and climate change. To produce food, feed, materials and energy, humans use biomass from various sources, including natural and managed ecosystems. Natural resources are the foundation on which the food system rests and biomass production plays a vital role in the development of the bioeconomy sector, supporting the transition from fossil fuels to renewable energy (Muscat *et al.*, 2021). However, current levels of biomass harvesting are associated with a variety of environmental issues that have to do with land use, biodiversity loss and climate change, among others (Krausmann *et al.*, 2013). As the global population continues to grow, the rising demand for biomass increases, compounding the problem. There is a growing recognition of the need to transform our economy, including our food systems, when it comes to biomass production and consumption as well as waste management (Steffen *et al.*, 2015; Rockström *et al.*, 2023), if we are to avoid further exceeding planetary boundaries.

Promoting a circular bioeconomy that operates within planetary boundaries is among the key strategies proposed by many countries to achieve this goal. To facilitate this, FAO has developed a global repository of bioeconomy policies reflecting societal aspirations, good governance principles, the need and opportunities to protect and valorize biomass, as well as scientific breakthroughs in biological, digital and other fields (FAO, 2024a).

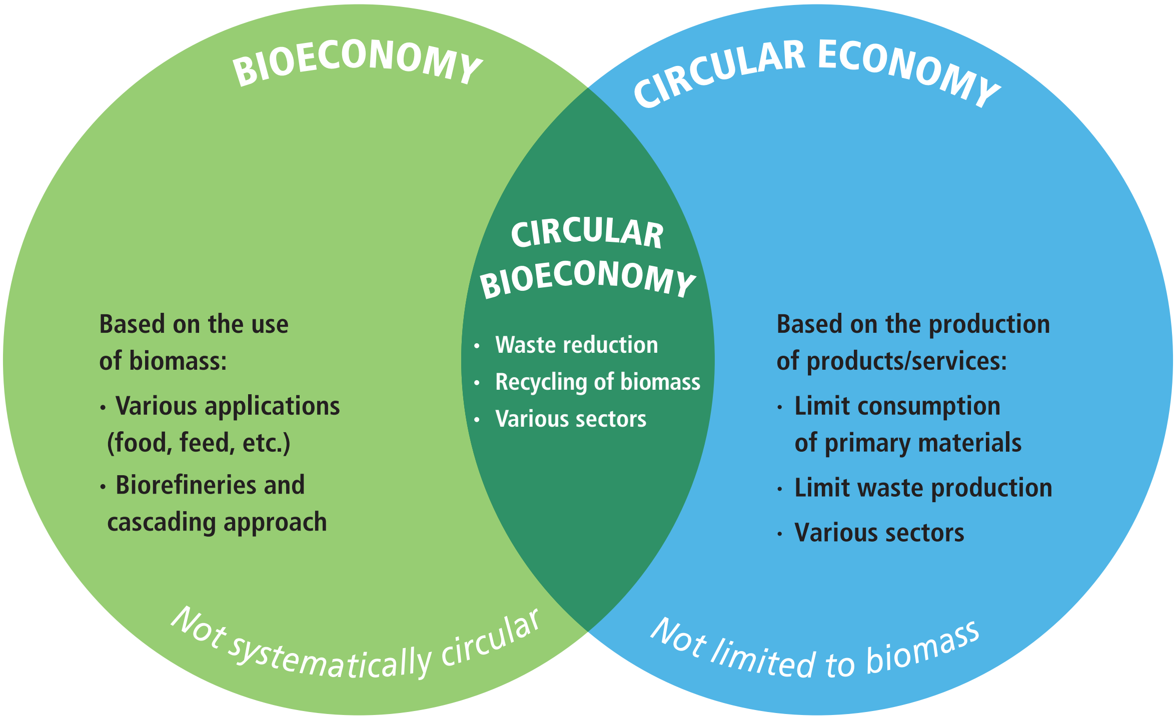
The 42nd Session of the FAO Conference defined bioeconomy as "the production, utilization, conservation and regeneration of biomass, including related knowledge, science, technology, and innovation to provide sustainable solutions (information, products, processes and services) within and across all economic sectors to enable a transformation to a sustainable economy" (International Advisory Council on Global Bioeconomy [IACGB] and the Global Bioeconomy Summit [GBS] Communiqué, 2020, p. 14). The bioeconomy involves sectors and interlinked systems that rely on biomass. This includes terrestrial and marine ecosystems, primary production sectors (crop and livestock production, forestry, fisheries and aquaculture), and all the activities that use biomass to produce food, feed, fibre, energy and other bio-based products and services (Gomez San Juan, Harnett and Albinelli, 2022). Therefore, the circular bioeconomy offers a conceptual framework for using renewable natural capital to transform and manage land, food, health and industrial systems, with the goal of achieving sustainable well-being in harmony with nature.

The bioeconomy addresses global, multidimensional challenges, but it is not inherently sustainable, as it risks perpetuating a linear economic model, one which favours short-term gain over long-term sustainability (Stegmann, Londo and Junginger, 2020; FAO, 2021a). Reichel, De Schoenmakere and Gillabel (2016) have argued that the circular bioeconomy uses biomass more efficiently and, above all, sustainably, as it allows for the regeneration of natural and/or managed (eco)systems. In a circular bioeconomy, products, components and materials that might otherwise be discarded are preserved to ensure that resources are used efficiently, whereas waste production is ideally designed out of the process at an early stage (Reichel, De Schoenmakere and Gillabel, 2016). According to the Ellen MacArthur Foundation, a circular economy is based on three principles: (1) eliminating waste and pollution; (2) circulating products and materials (at their highest value); and (3) regenerating nature.

A circular bioeconomy lies at the intersection of the bioeconomy and the circular economy (Figure 1), with an emphasis on the sustainable use of biomass through closed-loop systems that rely on reducing, reusing and recycling biomass. It provides ecosystem services that enable the sustainable production, use, conservation and regeneration of biomass, and their transformation into food, feed, fibre, fuel and other materials, while remaining within ecosystem boundaries. The circular bioeconomy aims to support sustainable well-being for society at large, based on healthy, biodiverse and resilient ecosystems (McGlade *et al.*, 2020). Achieving a resource-efficient circular bioeconomy is expected to generate USD 7.7 trillion for the global economy by 2030 (WBCSD, 2019).

At present, many agricultural and livestock activities contain elements that are intrinsically linear in nature. These activities involve the harvest of a certain amount of biomass from the system, in which a large proportion of inputs do not contribute to products directly consumed by humans, while generating losses and waste that have negative

FIGURE 1
**The integration of bioeconomy and circular economy frameworks into the circular bioeconomy**




*Source:* Authors' own elaboration.

consequences for the environment. Under this paradigm, achieving circularity in the food system amounts to searching for practices and technologies that minimize the input of finite resources (e.g. fossil fertilizers and fuels, water and land), encouraging the use of regenerative practices, and stimulating the reuse/recycling of residual streams (e.g. human and livestock excreta) in a way that adds the highest value to unavoidable food system residues (Ghisellini, Cialani and Ulgiati, 2014; Jurgilevich *et al.*, 2016; Corona *et al.*, 2019; Valls-Val, Ibáñez-Foré and Bovea, 2023).

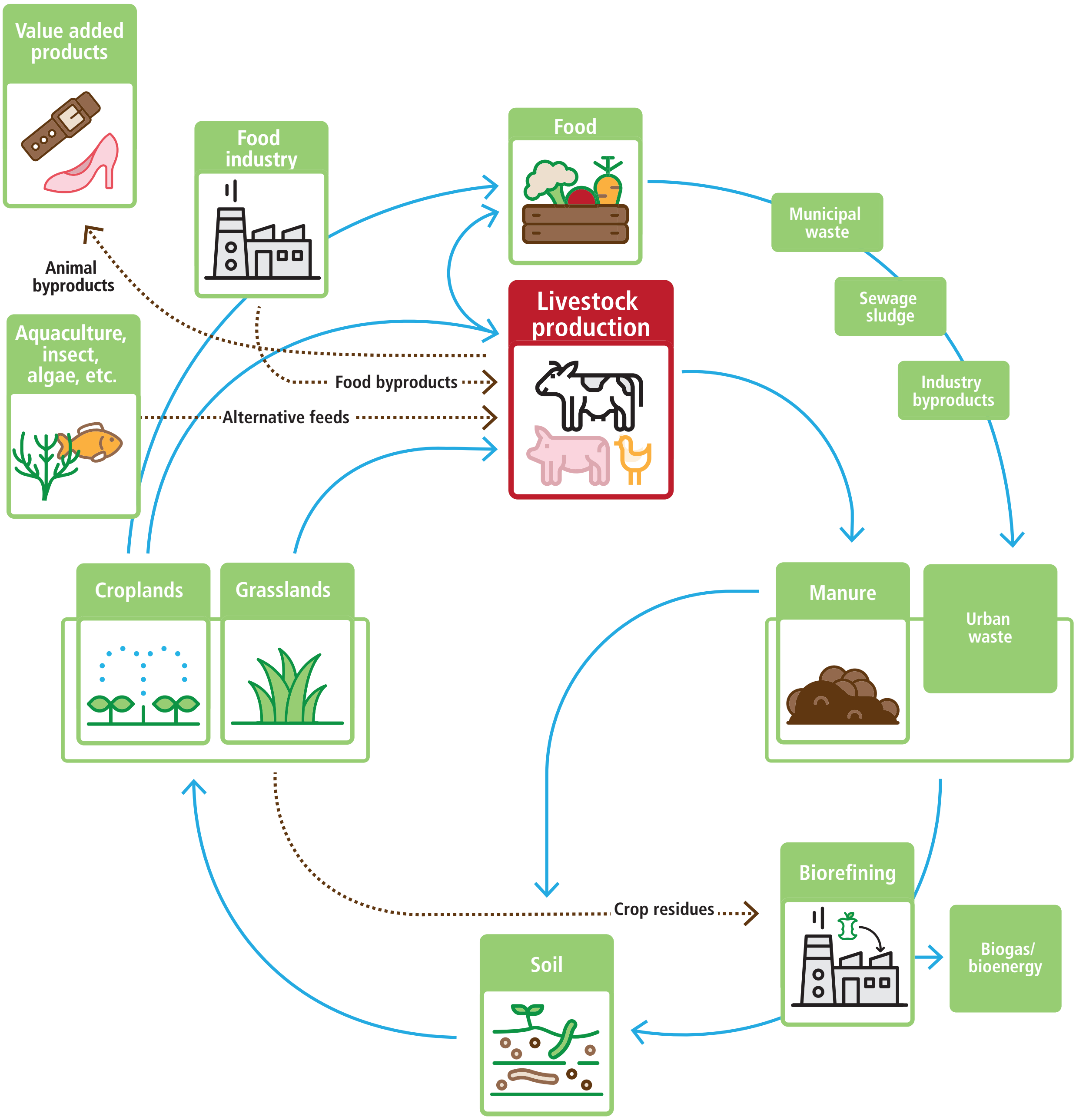
When stakeholders involved in livestock systems implement circularity practices, they must also take into account the accessibility and feasibility of adoption, as well as any implications for animal health and well-being (Perry, Robinson and Grace, 2018; Puente-Rodríguez, Van Laar and Veraart, 2022). Societal impacts and how human behaviour may influence the outcomes should also be considered (Corona *et al.*, 2019).

While the bioeconomy involves cross-sectoral collaboration at different levels, this document focuses on food systems – and specifically the role that the livestock sector plays in circularity (e.g. upcycling, recycling) – and considers how the concept of a circular bioeconomy can make livestock production more sustainable. Although the effective implementation of a circular bioeconomy for livestock would engage multiple ancillary sectors and value/supply chain components, such as transport, packaging and storage, the primary focus here is on the livestock production itself.

## 1.1 ROLE OF LIVESTOCK IN A CIRCULAR BIOECONOMY

In a circular bioeconomy, arable land is used primarily to produce food and materials for other needs (De Boer and Van Ittersum, 2018; Van Zanten, Van Ittersum and De Boer, 2019). During the production and consumption of food, residuals and co-products are generated from agricultural activities, industrial food processing, food losses and waste, and human and animal excreta. Preventing human edible co-products from becoming food waste is a priority. Under this paradigm, livestock are a crucial part of the circular bioeconomy by recycling resources that are not part of the primary food basket. This is accomplished through the production of food, the use of human non-edible plant-based products (PBPs), residual management, nutrient cycling, soil health, biodiversity and renewable energy generation (Figure 2). Livestock are also essential to the sustainability of integrated crop–livestock systems where the inclusion of forages in rotational cropping systems and the provision of manure contribute to carbon sequestration and soil health (Giacometti *et al.*, 2021). Thus, livestock play an important role in the circular bioeconomy by enabling the upcycling of

FIGURE 2
**Representation of circular bioeconomy for livestock systems**




*Source:* Adapted from Van Zanten, H.H.E., Van Ittersum, M.K. & De Boer, I.J.M. 2019. The role of farm animals in a circular food system. *Global Food Security*, 21, 18–22. https://doi.org/10.1016/j.gfs.2019.06.003

agricultural products that cannot be consumed by humans into valuable nutritional animal-sourced food (ASF) and producing manure as a fertilizer. Livestock can also be used to provide and deliver other ecosystem services and cultural values.

Animal-sourced food provides a significant portion of the world's food supply, including 34–40 percent of global protein consumption (FAO, 2023a; Smith *et al*., 2024). By utilizing non-edible biomass such as grasslands, crop residues, crops designated unsuitable for food and by-products from other industries (e.g. oilseed meals), animals can convert low-value resources into high-quality nutrient sources for human consumption (Tedeschi *et al*., 2015). This can promote circularity, provided that grassland is managed sustainably and that it makes a larger net contribution to circularity than other land uses such as the provision of food, feed, biomaterials and biodiversity conservation. Of the feed consumed by livestock, 86 percent is estimated to be unsuitable as food for humans, with the remaining 14 percent corresponding to one-third of global cereal production (Mottet *et al*., 2017). Under a circular paradigm, food–feed competition is avoided, while livestock systems recycle residual streams from food–feed production and bio-based industries.

Livestock also play a vital role in nutrient cycling and soil health, which are essential for the functioning of agroecosystems. Animals produce manure, a valuable organic fertilizer rich in macro- and micronutrients and in organic matter. Coupling crop and animal production at an adequate density, together with appropriate management of animal excreta as a nutrient source for crops, contributes to agricultural sustainability and reduces the need for synthetic fertilizers (Soussana and Lemaire, 2014). This closed-loop approach can help maintain soil fertility, promote soil health, increase nutrient cycling, enhance long-term crop productivity, and reduce production costs (Rufino *et al.*, 2006).

Owing to the linear nature of current industrial livestock and agricultural systems, not all system inputs contribute to products consumable by humans and generated residuals have the potential to cause pollution (FAO, 2023a). It is estimated that between USD 1 trillion and USD 2 trillion per annum are lost through inefficiencies in the global food economy, and as much as 31 percent of the food produced for human consumption is wasted (UNEP, 2024). Livestock production systems rarely produce a single product, raising the possibility that one commodity can add value to another through circularity (e.g. food by-products as feed for livestock or whey used to enhance fermentation in bio-based industries).

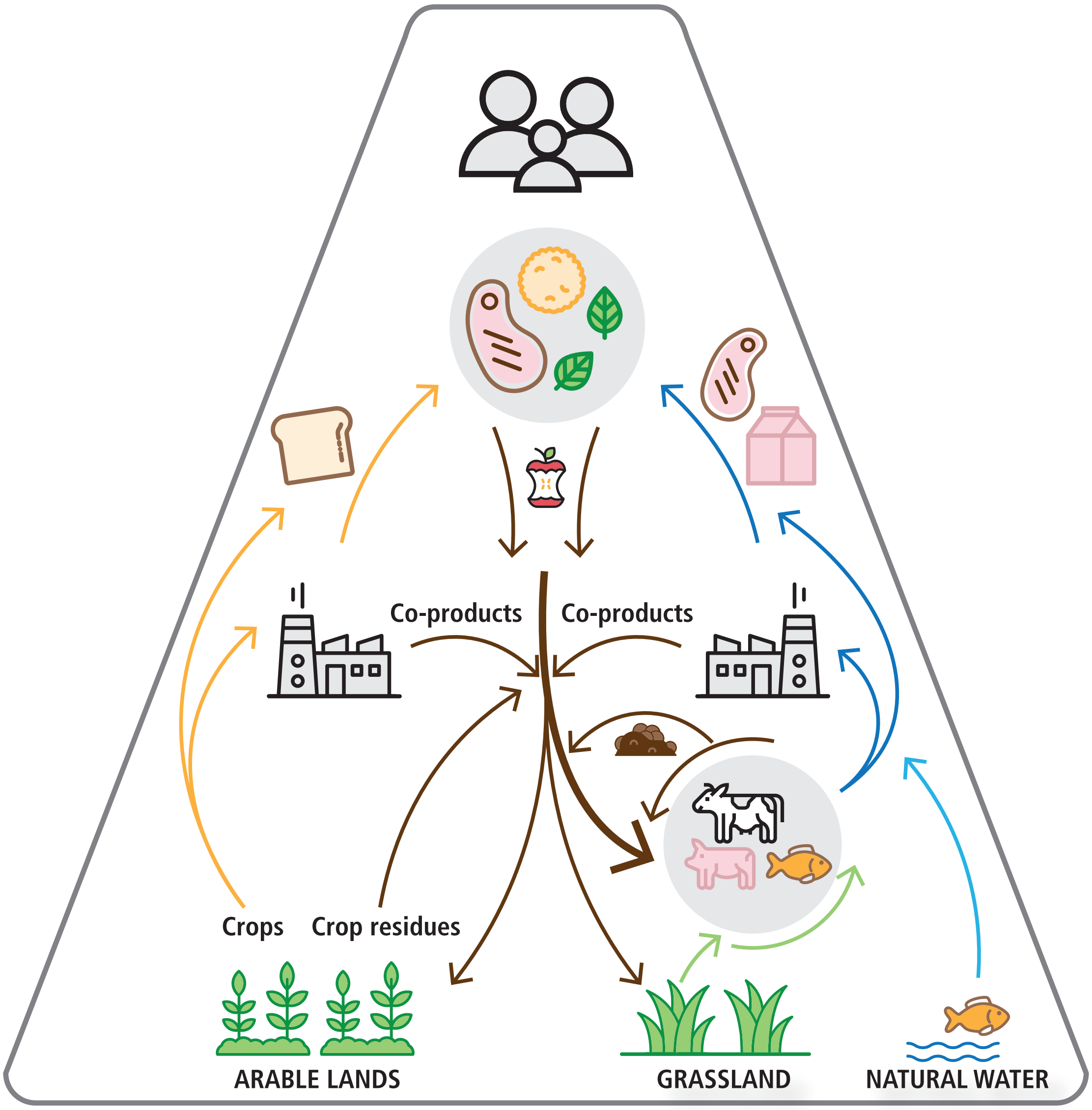
Livestock can recycle and upcycle resources while playing an important role in feeding humanity by consuming low opportunity cost by-products (LCB) and biomass from grasslands (Varijakshapanicker *et al.*, 2019). In a circular bioeconomy, livestock are fed biomass unsuitable for consumption by humans, thereby producing valuable ASF, animal-based products (ABP) (e.g. leather, wool), manure and other ecosystem services (Figure 3). The available biomass to feed livestock includes crop residues, co-products arising from the industrial processing of PBPs and ABPs or from other industrial processes (e.g. biofuel, fermentation), forages produced on lands less suitable for the cultivation of food crops, and food loss and residuals that are unsuitable for human consumption. By converting these LCB streams, livestock recycle nutrients back into the food system that otherwise would be lost. As a result, the food–feed competition for land is reduced (Van Zanten *et al.*, 2018; Wilkinson and Lee, 2018). Land used for agriculture constitutes about 38 percent of the global land area, one-third of this being dedicated to crop production and the remaining two-thirds used by grazing livestock (FAO, 2020). Of the available cropland, 40 percent is used to produce high-quality feed ingredients that humans can also eat, such as cereals, resulting in food–feed competition for land and other natural resources. As livestock require more energy (as a result of maintenance costs) than they generate as muscle, milk or eggs, they consume more calories from feed than they produce.

Food–feed competition can be direct or indirect. Direct competition occurs when biomass suitable for human consumption is fed to livestock instead of humans (Wilkinson and Lee, 2018). Indirect competition occurs when feed ingredients are cultivated in areas where crops for human consumption could be grown (Van Zanten *et al.*, 2016a). In both instances, land is allocated to produce biomass to feed livestock instead of humans. Whereas some livestock, including pigs and poultry, rely more on arable land for feed production, ruminants (e.g. sheep and cattle) may obtain nutrients by grazing lands less suitable for producing food for humans (Lee *et al.*, 2021). In terms of global food production, feeding animals more LCBs could significantly increase the global food supply, but possibly at the cost of a reduction in animal productivity, if diets are unbalanced. Sandström *et al.* (2022) estimated that, should feed ingredients such as cereals, fish by-catch, pulses and vegetable oil be replaced with food system co-products, global food availability would increase by 13 percent and by 15 percent in terms of kilocalories and protein, respectively. While kilocalories and proteins do not necessarily mean improved nutrition, they can contribute to improved food security and nutrition in many parts of the world. Redesigning the livestock sector based on circularity principles offers the opportunity to reduce food–feed competition, lower environmental impacts, improve the efficiency of water, energy and natural resource use, while contributing to global food security.

Manure from livestock is also a source of biomass for bioenergy generation, thus contributing to the circular bioeconomy. Anaerobic digestion (AD) of manure can generate biogas, a renewable energy source primarily composed of methane ($CH_4$). Biogas can be harnessed to produce heat and electricity, or further refined into $CH_4$ for injection into natural gas grids, or liquified for use as a transportation fuel. Converting manure into biogas simultaneously addresses residual management challenges, reduces GHG emissions and provides a renewable energy resource that reduces the reliance on conventional fossil fuels. Furthermore, the process produces a nutrient-rich digestate, which can be utilized as a fertilizer or subject to further refinement (Dubis, Szatkowski and Jankowski, 2022).

Animal-based products, including bones, hides and offal have numerous applications beyond traditional food

FIGURE 3
**The biophysical concept of circularity**

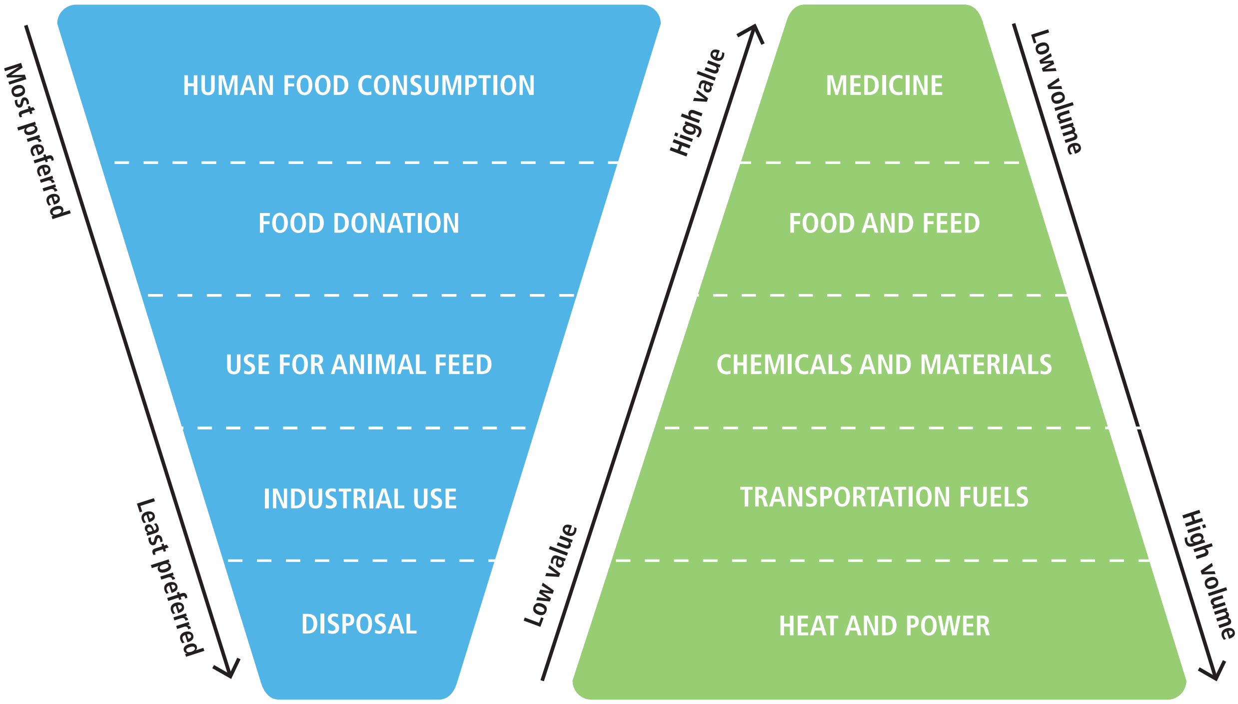



*Note:* Arable land is primarily used for food production; biomass unsuited for direct human consumption is consumed by animals. Some co-products and manure are used to maintain soil fertility. In this way, nutrients are recycled, and animals contribute to circularity and improve the sustainability of the food system.
*Source:* Van Zanten, H.H.E., Van Ittersum, M.K. & De Boer, I.J.M. 2019. The role of farm animals in a circular food system. *Global Food Security*, 21, 18–22. https://doi.org/10.1016/j.gfs.2019.06.003

production. These materials can be used to produce value-added products such as leather, gelatin, pet food and feed, pharmaceuticals, cosmetics and biodiesel. Moreover, many of these are rich in collagen, keratin and minerals, making them a source of high-value biochemicals and other biomaterials with various industrial applications.

The notion of valorizing ABPs abides by the principles of "food waste hierarchy" and "value pyramid" described by Zohairi, Trydeman Knudsen and Mogensen (2023; Figure 4). Sometimes these concepts are described as a "cascading use of biomass" (Dubois and Gomez San Juan, 2016). The preferred option is source prevention (i.e. avoiding the generation of food waste), followed by food recovery, where a greater proportion of plant or animal biomass is used or recovered as human edible food. The value pyramid then proposes the recycling of co-products to produce food through their use in feed, followed by the recovery of co-products for industrial applications. This can include the production of co-products ranging from pet foods and lower-value chemicals to materials such as fertilizers, soap or biodiesel. The ABPs can also be used as a substrate for biodigestion or combusted to produce bioenergy. Finally, when all other options have been exhausted, the remaining ABPs can be disposed of through combustion or landfilling.

FIGURE 4
**Hierarchy and value pyramid of animal-based products from slaughterhouses**




*Source:* Zohairi, S.Al., Trydeman Knudsen, M. & Mogensen, L. 2023. Utilizing animal by-products in European slaughterhouses to reduce the environmental footprint of pork products. *Sustainable Production and Consumption*, 37, 306–319. https://doi.org/10.1016/j.spc.2023.03.005

## 1.2 CONTRIBUTION OF LIVESTOCK TO THE SUSTAINABLE DEVELOPMENT GOALS

FAO Members have endorsed bioeconomy as a Programme Priority Area in FAO's Strategic Framework for 2022–2031. While the bioeconomy has an impact on all the SDGs, bioeconomy practices themselves are not inherently sustainable.

When governments develop policies and strategies to foster a sustainable bioeconomy, they establish a foundation for bio-based research, technological innovation, education, capacity building, industrialization, inclusive development in rural and urban areas, consumer demand creation and greater societal awareness. It is crucial to carefully consider any trade-offs between these elements and other sustainability goals. Target 12.2 ("By 2030, achieve the sustainable management and efficient use of natural resources."), Target 12.4 ("By 2030, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment.") and Target 12.5 ("By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse.") align with FAO's Programme Priority Areas (FAO, 2021a). While every country has the potential to develop a bioeconomy based on its unique biomass resources, not all have strategies in place to coordinate across sectors or to address resource competition and sustainability trade-offs. FAO has developed a framework of 10 Aspirational Principles and 24 Criteria for a Sustainable Bioeconomy aligned with the SDGs. Central to FAO's bioeconomy efforts, these principles and criteria encourage a comprehensive approach that integrates the social, economic and environmental dimensions of sustainability, and pays heed to good governance (Bracco *et al*., 2019). Aimed at policymakers and stakeholders, these principles and criteria guide the development of bioeconomy policies and sustainability assessments, with a particular emphasis on the inclusion of smallholders.

When managed sustainably, livestock systems in a circular bioeconomy are not only compatible with the SDGs; they are essential for achieving a holistic, systems-based approach to global sustainability. By converting inedible biomass – such as crop residues, food processing by-products and pastures unsuitable for cultivation – into nutrient-dense animal-sourced foods, livestock in a circular bioeconomy contribute directly to **SDG 2 (Zero Hunger)**. They also return organic matter to soils, improve fertility and reduce reliance on synthetic fertilizers, thereby promoting **SDG 12 (Responsible Consumption and Production)**. When directed to reduce methane and nitrous oxide emissions and enhance soil carbon sequestration, this nutrient-cycling function further supports **SDG 13 (Climate Action)**. Moreover, livestock provide livelihoods for over a billion people, especially in rural and marginalized communities, advancing **SDG 1 (No Poverty)** and **SDG 8 (Decent Work and Economic Growth)**. Integrated into agroecological and regenerative systems, livestock help sustain grasslands, foster biodiversity and improve soil health, aligning with **SDG 15 (Life on Land)**.

Given that each country and region faces unique challenges and opportunities in biomass use – shaped by their political, social, economic, industrial and technological context, as well as the availability of natural resources – a one-size-fits-all solution does not apply. Instead, tailored interventions are necessary to address the specific needs and circumstances of different countries and regions. In support of circular bioeconomy systems in the livestock sector, FAO has identified sources of unavoidable waste that can be repurposed as by-products, mapped plants that grow in marginal areas or require fewer fertilizers, and made an inventory of plant-protections products suitable for the cultivation of feed ingredients (FAO, 2022). Other interventions include the use of insect-based feed ingredients, the incorporation of microbiome management in livestock within the One Health framework, and improved breeding and livestock management. These practices aim to reduce the negative environmental impact of animal production, while generating socioeconomic benefits for communities.

## 1.3 OBJECTIVES AND SCOPE OF THE DOCUMENT

It is recognized that the livestock sector can play a socioeconomic role in supporting sustainability through circularity, a practice that is frequently more developed in low- than in high-income countries (Paul *et al.*, 2020). By promoting a more efficient use of biomass and energy through the reuse and recycling of residuals, a circular bioeconomy aims to reduce the consumption of resources and make biomass production more efficient. These guidelines seek to provide information on the measurements and product uses for strengthening circularity within the livestock sector. The document outlines the possible interactions, trade-offs and roles that livestock play within the framework of a circular bioeconomy.

With this in mind, based on existing, widely used metrics and indicators, this document gives a brief overview (Section 2) of the methods available to assess the environmental impact of livestock production in a circular bioeconomy, touching on the advantages and disadvantages of each method. Section 3 conducts a review of PBP (Section 3.1) and ABP use (Section 3.2), before considering how residuals such as manure (Section 3.3) are valorized in the context of a circular bioeconomy. The guidelines provide intended users and decision-makers with examples of recovery options and bioeconomy innovations rooted in specific regional contexts. Section 4 goes on to explore the political and regulatory implications of policies promoting circular economy and bioeconomy, along with their main strengths and limitations when it comes to supporting the use of PBPs, ABPs and residuals.

This document is intended for a broad range of livestock stakeholders, including producers, supply-chain partners (e.g. feed producers), livestock farming organizations, processors of animal products and retailers who are working to improve the environmental performance of their production systems. Non-livestock stakeholders seeking to collaborate with the livestock sector through recycling or upcycling of residuals and waste stand to benefit from its insights, as do policymakers interested in promoting and developing circular bioeconomy strategies for livestock supply chains. The guidelines are designed for individuals or organizations with a sound working knowledge of the environmental assessment of livestock systems, based on the life cycle assessment (LCA) methodologies.

# Chapter 2
# Methodologies and their application

## 2.1 INDICATORS TO ASSESS THE ROLE OF LIVESTOCK IN CIRCULAR FOOD SYSTEMS

In this chapter, we first go over the methods available to assess the environmental impact of livestock production in a circular bioeconomy, and consider the advantages and disadvantages of each method. Circularity may involve a set of practices aiming to reduce the environmental impact of livestock. As these practices are often necessarily country- or region-specific, not all indicators are relevant to all food systems (Lebacq, Baret and Stilmant, 2013). Schreefel *et al.* (2023) identified four main types of indicators relevant for assessing the role of livestock in circular livestock systems: target-based, result-based, practice-based and outcome-based. Each indicator comes with a specific set of measurements that are used to assess the impact of practices on the sustainability of livestock production.

Target-based indicators focus on the presence of a plan to implement one or more interventions, as outlined in the European Commission's New Circular Economy Action Plan or the FAO dashboard *Sustainable bioeconomy for agrifood systems transformation*. The European Commission stressed the need for a monitoring framework, such as the EU monitoring framework for the bioeconomy or the monitoring framework for a circular economy, to transition to a circular bioeconomy. Several result-based indicators were identified within the "monitoring framework for a circular economy" (e.g. food waste per kg or capita), which are monitored with the overall aim of contributing to a more sustainable food system. National goals and targets are often linked to SDGs, and countries use indicators adapted to them. Corona *et al.* (2019) described result-based indicators as "circularity measurement indices". These indices measure the degree of circularity (0–100 percent), based on the assumption that higher circularity results in a lower environmental impact. Another example is the "new product-level circularity metric" proposed by Linder, Sarasini and Van Loon (2017, p. 545), in which circularity is defined as "the fraction of a product that comes from used products".

Result-based indicators generally focus on one or a few aspects of circularity at different operational scales. These indicators should reflect the intermediate consequences or impact of certain interventions/practices on outcomes/goals, such as monitoring the reduction of food–feed competition by feeding livestock with more food residuals or non-edible biomass. It is important to ensure that the measurement methodologies consider all direct and indirect impacts of a practice, so that result-based indicators achieve their intended consequencesm for example a reduction in food–feed competition leading to a reduction in carbon dioxide-equivalent ($CO_2$e) emissions at the farm, regional, national or international level.

Practice-based indicators measure the degree of implementation of an intervention. Practice-based indicators are often used in certification schemes, as with organic agriculture. However, feeding livestock more food residuals does not guarantee a reduction in food–feed competition since the share of food residuals might increase, while the share of co-products decreases. Consequently, implementing a certain practice does not automatically result in a favourable outcome, as its success often depends on socioeconomic circumstances and environmental conditions. Measuring the success of practice-based indicators by means of result-based indicators (or indices) is important. For example, reclaiming food waste from landfills to use it as livestock feed could result in a reduction of GHG emissions from food systems (Mengistu *et al.*, 2025).

Outcome-based indicators, referred to as "circularity assessment tools" by Corona *et al.* (2019), assess interventions based on the extent to which they reach their targeted goals (Corona *et al.*, 2019; Schreefel *et al.*, 2023) but are generally complex to assess. An outcome-based indicator assesses the environmental change brought about by the implementation of a practice. For example, feeding more food residuals may or may not result in a limited reduction of the environmental impact, if food residuals are captured higher up the value pyramid (Van Zanten *et al.*, 2016b). Feeding more co-products to livestock does not necessarily reduce the environmental impact, especially if policy incentives result in a rising demand for the co-product put to a different use. Alternatively, redirecting co-products for use as feed may lower the environmental impact, if they were originally destined to be landfilled or incinerated. Implementing circularity often results in a systematic change and studies have shown that some interventions can have unintended consequences (Corona *et al.*, 2019; Latka *et al.*, 2022).

Researchers have used three methods – nutrient use efficiency (NUE) (Section 2.2.1), attributional and consequential

LCA (Section 2.2.2), and integrated models such as food systems modelling (Section 2.2.3) – to assess various environmental indicators across different scales and system boundaries, ranging from farms to entire food systems. We have focused on these methods because of their widespread use and proven effectiveness in measuring the environmental impact of the livestock sector within the bioeconomy.

### 2.1.1 Circularity indicators for nutrient use efficiency

In circular systems the loss of nutrients (e.g. nitrogen [N], phosphorus [P]) is minimized while residual streams (e.g. human and livestock excreta) are reused and recycled in ways that add the highest value (Ghisellini, Cialani and Ulgiati, 2014; Jurgilevich *et al.*, 2016; Corona *et al.*, 2019; Valls-Val, Ibáñez-Foré and Bovea, 2023). One way to measure the NUE is by adopting the nutrient balance approach (Oenema, Kros and De Vries, 2003), which assesses the difference between nutrients entering and leaving the system. As in LCA, the system boundaries and a functional unit need to be defined to establish a nutrient balance. Based on the nutrient balance, the NUE can be calculated as the amount of nutrients leaving the system divided by the amount of nutrients retained in the system (Nevens *et al.*, 2006). The nutrient balance also allows the nutrient surplus from the system to be expressed per hectare land or per kg output product. When quantifying the input and output flows one can also estimate the "recycling" flows within the system to generate an estimate of the degree of circularity (FAO, 2018b). For example, a mineral fertilizer would be considered as a new input into the system, while animal manure and biologically fixed nitrogen (N) would be considered a recycled (atmospheric) input. According to FAO LEAP guidelines (2018), nutrient circularity can also be analysed from the perspective of either input or output flows. This approach distinguishes between "new" inputs, which include mineral fertilizer and biological fixation, and "recycled" inputs originating from external sources or in the same supply chain (atmospheric deposition, organic fertilizers, animal manure or feed co-products). For outputs, it distinguishes between products intended for "consumption" (co-products) and residual flows that are recycled back into the system (Box 1).

An example of the use of NUE for a dairy farm in Denmark is provided in Box 2.

BOX 1
**Analysis of nutrient circularity**

**Partial nutrient balance (PNB):**
PNB = IN - ON,
where IN is the sum of nutrients in inorganic and organic inputs, such as imported fertilizer or feed, and ON is the sum of nutrient outputs like milk, livestock or harvested crops.

**Nutrient use efficiency (NUE):**
NUE = (ON/IN)* 100
where NUE is the ratio between the harvested outputs (ON) and managed inputs (IN).

**Gross nutrient surplus (GNS):**
GNS = (IN - ON)/area
where GNS is calculated as the difference between total nutrient inputs (IN) and total nutrient outputs (ON) at a land or production unit level. GNS is expressed in kg of nutrients per hectare of agricultural land. The area and flows are quantified with respect to the boundaries of the system (e.g. farm).

**Nutrient recycling index (NRI):**
NRI = NR/(IN + NR)
where NRI is the proportion of total recycled nutrients (NR) for total nutrient inputs (IN).

**Circularity indicator for inputs ($I_{Circ}$):**
$I_{Circ} = (F_{i,rec} + F_{rec})/(F_{i,new} + F_{i,rec} + F_{rec})$
where $I_{Circ}$ is the circularity indicator for input, $F_{i,rec}$ are the "recycled" inputs originating from external sources, $F_{rec}$ are the recycled inputs from the system, and $F_{i,new}$ are the new inputs in the system.

**Circularity indicator for outputs ($O_{Circ}$):**
$O_{Circ} = (F_{res} + F_{rec})/(F_{cp} + F_{res} + F_{rec})$
Where $O_{Circ}$ is the circularity indicator for output, $F_{res}$ are the residual flows that are recycled, $F_{rec}$ are the flows that are recycled, and $F_{cp}$ are the flows that are intended for consumption.

### 2.1.2 Life cycle assessment

Life cycle assessment is an internationally accepted and standardized method for evaluating the environmental impact along the entire production chain. To assess an environmental impact such as land use, LCA studies rely on a predefined functional unit such as the amount of land used to harvest a certain crop- or animal-sourced product. The functional unit can be a kg of harvested grain or a kg of protein from eggs, but it is important to ensure that the chosen functional unit truly reflects the value of the product across multiple sustainability parameters (Manzano *et al.*, 2023) and/or its nutritional value (McAuliffe, Takahashi and Lee, 2020). The system boundaries can range from a farm

BOX 2

**The use of nutrient use efficiency (NUE) to assess Danish dairy farms sustainability**

There are various ways of evaluating the efficiency of nutrient cycling on a farm. Van Loon *et al.* (2023) contributes to the discussion on the relative contribution of new or circular nutrients to equilibrium efficiency. One metric proposed is the use count, which is the average number of times a nutrient cohort passes through the top trophic level that produces the output of the system. An additional metric, the cycle count is used to determine the relative contributions of either direct or cycled nutrient flow to the output–input flow based on the average number of cycles a nutrient cohort completes before it exits the system.

Taken together, these metrics help quantify the relative contribution of cycle nutrients to NUE. For example, a Danish dairy farm imports significant feed quantities to supplement feed grown on the farm. The analyses showed that there were substantial differences in the level of circularity between nitrogen (N) and phosphorus (P) on the farm. The overall output–input (O/I) ratio for N was 0.28, where only 35 percent (0.10) was from cycle flow. This was, in part, the result of large losses of N during manure storage and when it was used as fertilizer for feed production. The overall O/I ratio was 0.72 for P, where 60 percent (0.43) was from cycle flow. This reflects far lower levels of environmental leakage, with 85 percent of P input to soil coming from applied manure. In contrast, only 50 percent of the N input to soils came from manure. This difference in circularity is supported by the cycle count metric (N = 0.54 and P = 1.49) and the use count metric (N = 1.11 and P = 2.39). Based on these results, P not only has a higher nutrient use efficiency than N, but is also more readily retained and cycled on the farm. The metrics in this case study contrast the conclusions that can arise in the NUE of different nutrients at the farm level.

*Source:* Van Loon, M.P., Vonk, W.J., Hijbeek, R., Van Ittersum, M.K. & Ten Berge, H.F.M. 2023. Circularity indicators and their relation with nutrient use efficiency in agriculture and food systems. Agricultural Systems, 207, 103610. https://doi.org/10.1016/j.agsy.2023.103610

to a complete value chain, covering various aspects of the bioeconomy. Life cycle assessment can also evaluate a product for mid-point (e.g. GHG emissions) or end-point effects (e.g. contribution to climate change) (Röös, Sundberg and Hansson, 2010; Karlsson Potter and Röös, 2021).

There are two types of LCA: attributional LCA (ALCA) and consequential LCA (CLCA). Whereas ALCAs provide information about the status quo, CLCAs provide information about the potential impact of changing the status quo.

#### *2.1.2.1 Attributional life cycle assessment*

An ALCA describes the environmentally relevant physical flows to and from a product or system (Klöpffer, 2006). For each process of the system, the related environmental impact is determined and the impact of all processes is summed to assess the environmental impact on the system. Attributional life cycle assessments implicitly combine information about crop productivity (i.e. crop yield per hectare) and animal productivity (i.e. feed efficiency along the chain, including breeding, rearing and production). Analyses often address outcomes, such as increasing crop yield per input of natural resources, the amount of pollutants lost to the environment, strategies to increase feed efficiency and lifetime productivity or to combat disease. They can include strategies designed to reduce GHG emissions from livestock production systems, the impact of changing diet formulations and the value of reducing losses along the production chain. Results can be used to compare livestock production practices and to identify hotspots and potential opportunities for improvement. The Product Environmental Footprint recommended by the European Union and the LEAP guidelines adopt an ALCA approach with specific standards on the environmental impact of agriculture from production to processing – including transportation, packaging and end-use – to generate a product footprint across its entire lifecycle (FAO, 2018b; European Commission, 2021; EUROSTAT, 2023).

#### *2.1.2.2 Consequential life cycle assessment*

A CLCA describes how environmental flows/processes change within and beyond a product's production cycle in response to changes in the system (Ekvall and Weidema, 2004). Conducting a CLCA involves anticipating the consequences of an action, and therefore relies on a detailed understanding of cause-and-effect chains, which are subject to the uncertainty and complexity of socioeconomic dynamics. While CLCA methods have been used to assess the environmental impact of an increased demand for a product (Weidema, Ekvall and Heijungs, 2009), Van Zanten *et al.* (2014) developed a framework to determine the environmental impact of using LCB in livestock nutrition.

#### *2.1.2.3 Difference between attributional and consequential life cycle assessments*

One of the main differences between the ALCA and the CLCA lies in how they handle multifunctional processes. This is highly relevant for assessing the potential of circular food systems in multifunctional production processes that generate co-products. An example of a multifunctional process is sunflower production, where the main output is oil while the meal and the hulls are considered co-products.

Despite it being recognized that allocating environmental impacts among multifunctional processes should be avoided through system expansion, it remains a common practice in ALCA. Environmental impacts are allocated between outputs based on their underlying physical relationships, such as their relative weight or energy content (i.e. a natural science-based approach) or their relative economic value through "economic allocation" (i.e. a socioeconomic approach) (see Table 1). In the case of sunflower production, the greater the relative economic value of the main product (i.e. oil), the higher the environmental impact per kg product and the lower the environmental impact of the co-product (e.g. meal). Therefore, the environmental impact of a certain food item and its co-product(s) also depends on its economic value. When allocation is based on the share of edible food (in line with the circularity principle), the distribution of environmental impact among co-products changes. If the oil alone were suitable for human consumption, it would bear the full environmental impact (Table 1). Thus, the method of allocation has a major impact on the results.

In CLCA, system expansion is generally used to deal with multifunctional processes (Figure 5). System expansion includes any changes in the environmental impact associated with the alternative production process for which the co-product could be used. This is achieved by subtracting the impact of the alternative production process from the overall impact (Ekvall and Finnveden, 2001). A CLCA is recommended to assess the net environmental impact of a potential mitigation strategy where changes in production occur (Van Zanten *et al.*, 2018). For example, an increased use of wheat middlings in the diet of dairy cows may reduce the environmental footprint of milk and meat. However, if the supply of wheat middlings is thereby exhausted, wheat middlings will need to be replaced in the diet of other livestock species (e.g. pigs) by another feed ingredient such as whole wheat (Van Zanten, 2014). This could have the undesirable effect of increasing food–feed competition (Figure 5). Hence, CLCA may be better suited for evaluating the impact of sector changes on the overall food system.

**Issue 1.** Economic allocation does not address the full implications of dealing with product packages. For one thing, it does not account for the co-product's dependency on the production of the primary product (i.e. the demand for wheat flour impacts the production of wheat middlings). Moreover, co-products may already perform other functions that modify their environmental impact depending on the sector using them. Whether or not this results in an improved net environmental impact hinges on the environmental benefits of using the co-product in its new application, minus the environmental cost of replacing it in its prior application (Figure 5).

**Issue 2.** Allocation methods and system expansion do not consider whether a product is suitable for human consumption, nor do they account for livestock consumption of human-edible products or differences in the suitability of land for feed versus food production. One tangible way to consider the food–feed competition for land is to compute human-edible energy and protein conversion ratios (Wilkinson, 2011; Dijkstra *et al.*, 2013; Lee *et al.*, 2021), given that energy and protein are significant nutritional components. However, an important caveat is that even these computations do not reflect the full contribution of other nutrients (e.g. minerals and vitamins) that are nutritionally important to humans. Such analyses can be performed (Mazac, Järviö and Tuomisto, 2023) but are time-consuming.

### 2.1.3 Food systems modelling and circularity

The issue of allocation can be addressed by using integrated food and bioeconomy system models (Manzano *et al.*, 2023). Food system studies can yield different conclusions to those reached in LCA studies. For example, LCAs suggest that a vegan diet amounts to the lowest land use (Van Zanten, 2018; Scarborough *et al.*, 2023), while food system models reach a different conclusion (Van Zanten *et al.*, 2018).

Attributional life cycle assessments lend themselves to assessing the environmental impact of a specific production chain within set parameters. Assessing the environmental impact of livestock fed inedible biomass requires a complete

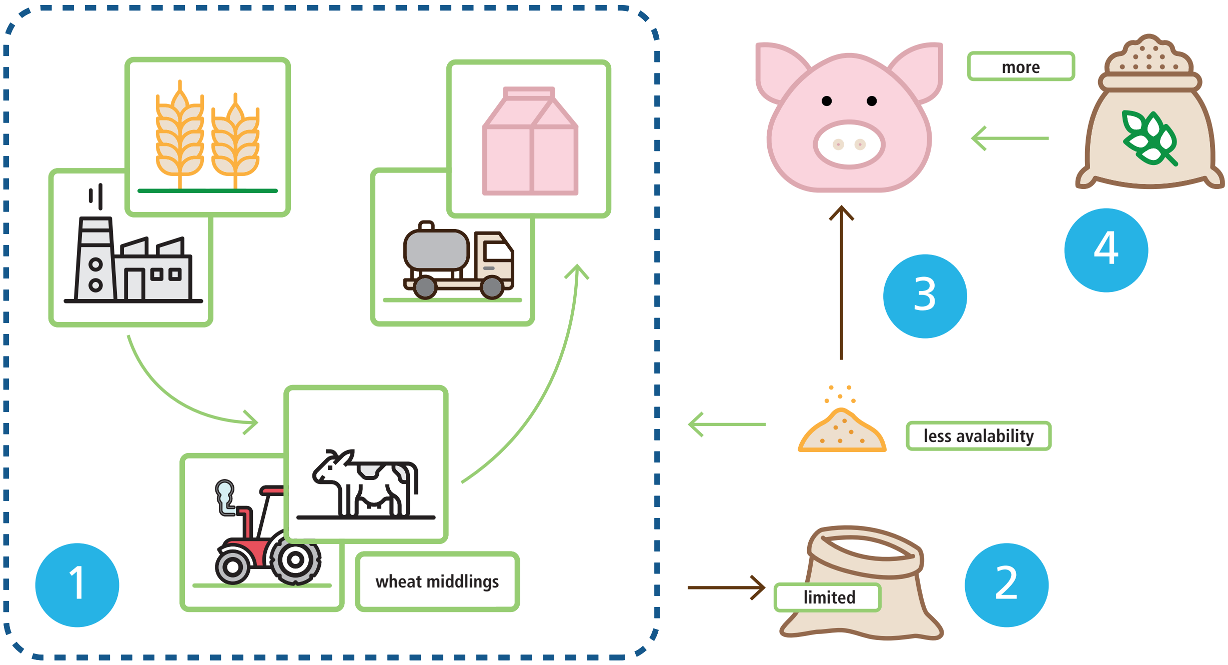
TABLE 1

**Environmental impact allocation of the co-products, resulting from the multifunctional process of sunflower seed crushing under economic and circular allocation**

| Oil extraction process | | Prices | Allocation | |
|---|---|---|---|---|
| Input | Output | (GBP/kg) | Economic | Circular |
| Sunflower seed | Oil | 1.15 | 88% | 100% |
| | Meal | 0.18 | 12% | 0% |
| | Hulls | 0.00 | 0% | 0% |

*Note:* Adapted from Van Hal, O., Weijenberg, A.A.A., De Boer, I.J.M. & Van Zanten, H.H.E. 2019. Accounting for feed-food competition in environmental impact assessment: Towards a resource efficient food-system. Journal of Cleaner Production, 240, 118241. https://doi.org/10.1016/j.jclepro.2019.118241

FIGURE 5
**Example of system expansion where allocation is avoided**




*Note:* In the case of a system expansion where allocation is avoided, the status quo changes as dairy cattle are fed a diet containing wheat middlings (1) as a circularity practice. If the amount of wheat middlings is limited (2), it means that increased use in dairy will reduce their availability for use by pigs (3). Consequently, pigs would need to be fed a feed containing another feed ingredient (e.g. wheat) (4), shifting the environmental impact from one sector to another but without significantly reducing the overall impact.

*Source:* Van Zanten, H.H.E., Oonincx, D.G.A.B., Mollenhorst, H., Bikker, P., Meerburg, B.G. & De Boer, I.J.M. 2014. Can environmental impact of livestock feed be reduced by using waste-fed housefly larvae? In: Schenck, R. & Huizenga, D., eds. Proceedings of the 9th International Life Cycle Assessment of Foods Conference in the Agri-Food Sector (LCA Food 2014), 1455–1461. Vashon, USA, ACLCA. https://lcafoodconferencearchives.hub.inrae.fr/content/download/3493/33807?version=1

redesign of the food system. Redesigning livestock systems based on circularity will not only impact the livestock sector itself but it will also modify the nature of human diets and crop production systems. To better understand the environmental impact and the role of livestock in circular food systems, we need to connect production (livestock and crops) with consumption in a holistic, integrated food systems approach (Karlsson *et al.*, 2020; Latka *et al.*, 2022; Van Zanten *et al.*, 2023).

Integrated models such as the ones described by Karlsson *et al.* (2020), Van Zanten *et al.* (2023), Latka *et al.* (2022), and Kopainsky and Kapmeier (2023) explicitly consider the intrinsic links between different products generated through multifunctional processes, such as wheat flour and wheat middlings from wheat production or milk and meat from dairy production. Such studies forgo allocating environmental impacts to each individual product within a multiproduct system. For the livestock sector, this is particularly relevant in relation to milk and meat in dairy production as well as for eggs and meat in layer production systems.

Accounting for interlinkages between the different products is especially important when designing future food systems (Van Zanten *et al.*, 2023; Kopainsky and Kapmeier, 2023). Integrated models are often referred to as food system models, as they use computer simulations to generate modelled scenarios within certain environmental or economic limits (Ericksen *et al.*, 2010). These modelled scenarios could include predetermined diets, such as the EAT–Lancet reference diet, which outlines a global, healthy and environmentally sustainable dietary pattern, or changes in production or consumption resulting from external shocks, such as climate change or a pandemic. In addition, food system models can be designed to incorporate economic variables, including changes in population or income level, or environmental factors, such as limiting GHG emissions or land use change (LUC) related to shifts in production systems (Jones *et al.*, 2017).

The role and aim of these models vary according to their scale and use. As a platform for exploring possible future food system scenarios, they can inform the scientific dialogue around food science. They can also provide information on the impact of different policy decisions, observed or projected economic changes. Food systems can be represented as general equilibrium, partial equilibri-

BOX 3

**Case study: The use of metrics for attributional life cycle assessment**

To evaluate the environmental impact of the main products and co-products of a process, while considering the circular use of co-products, the following two-step approach is proposed:

1. The circularity of each co-product is first defined, using the parameters provided in Box 1 and reflecting the priorities outlined in Figure 4.
2. Once the circularity allocation has been conducted, factoring in the environmental impact related to waste, the economic allocation is applied.

Four uses of a co-product are considered: i. combustion for heat; ii. biodiesel production and use of residuals as fertilizer; iii. use as feed to preserve nutrients; and iv. waste in landfill – under three scenarios described in the tables below:

- Scenario 1: a portion of the co-product is discarded as waste;
- Scenario 2: the portion that was wasted is upgraded to a partially circular co-product;
- Scenario 3: the portion that was wasted is upgraded to a fully circular co-product.

| Scenario 1 | Main product | Co-product 1 | Co-product 2 | Co-product 3 | waste |
|---|---|---|---|---|---|
| MA | 60% | 15% | 10% | 10% | 5% |
| Circ | N/A | 0% | 25% | 100% | N/A |
| CA | N/A | 100% | 75% | 0% | N/A |
| EA | 60% | 10% | 5% | 25% | 0% |
| EI/unit | 5 000 | 2 000 | 1 000 | 1 500 | 2 000 |
| EI process total | | 300 | 100 | 150 | 100 |
| EI MPcorr | 5 100 | | | | |
| Allocation | 4 398.75 | 510 | 191.25 | 0 | N/A |
| EI total | 4 398.75 | 810 | 291.25 | 150 | N/A |
| EI intensity | 7 331.25 | 5 400 | 2 912.5 | 1 500 | N/A |

| Scenario 2 | Main product | Co-product 1 | Co-product 2 | Co-product 3 | waste |
|---|---|---|---|---|---|
| MA | 60% | 15% | 15% | 10% | 0% |
| Circ | | 0% | 25% | 100% | N/A |
| CA | | 100% | 75% | 0% | N/A |
| EA | 59% | 10% | 7% | 24% | N/A |
| EI/unit | 5 000 | 2 000 | 1 000 | 1 500 | N/A |
| EI process total | | 300 | 150 | 150 | N/A |
| EI MPcorr | 5 000 | | | | N/A |
| Allocation | 4 207.5 | 500 | 292.5 | 0 | N/A |
| EI total | 4 207.5 | 800 | 442.5 | 150 | N/A |
| EI intensity | 7 012.5 | 5 333.3 | 2 950 | 1 500 | N/A |

| Scenario 3 | Main product | Co-product 1 | Co-product 2 | Co-product 3 | waste |
|---|---|---|---|---|---|
| MA | 60% | 15% | 10% | 15% | 0% |
| Circ | | 0% | 25% | 100% | N/A |
| CA | | 100% | 75% | 0% | N/A |
| EA | 52% | 10% | 4% | 34% | N/A |
| EI/unit | 5 000 | 2 000 | 1 000 | 1 500 | N/A |
| EI process total | | 300 | 100 | 225 | N/A |
| EI MPcorr | 5 100 | | | | |
| Allocation | 4 350 | 500 | 150 | 0 | N/A |
| EI total | 4 350 | 800 | 250 | 225 | N/A |
| EI intensity | 7 250 | 5 333.3 | 2 500 | 1 500 | N/A |

*Note:* MA = mass allocation; Circ = co-product circularity; CA = allocation on the basis of circularity (1 – Circ); EA = economic allocation; EI/unit = environmental impact of the addition process for the co-product (e.g. for feed drying); EI process total = total environmental impact of the process applied to the co-product (EI/unit * MA); EI MPcorr = environmental impact of the main product corrected by the impact of the wasted co-product (EI MP + EI process waste); Allocation = environmental impact allocated based on circularity and economic allocation (EI MPcorr * EA * CA); EI Total = environmental impact of the product and co-product (Allocation + EI process total); EI intensity = intensity of the environmental impact per kg product (EI total/MA).

BOX 4

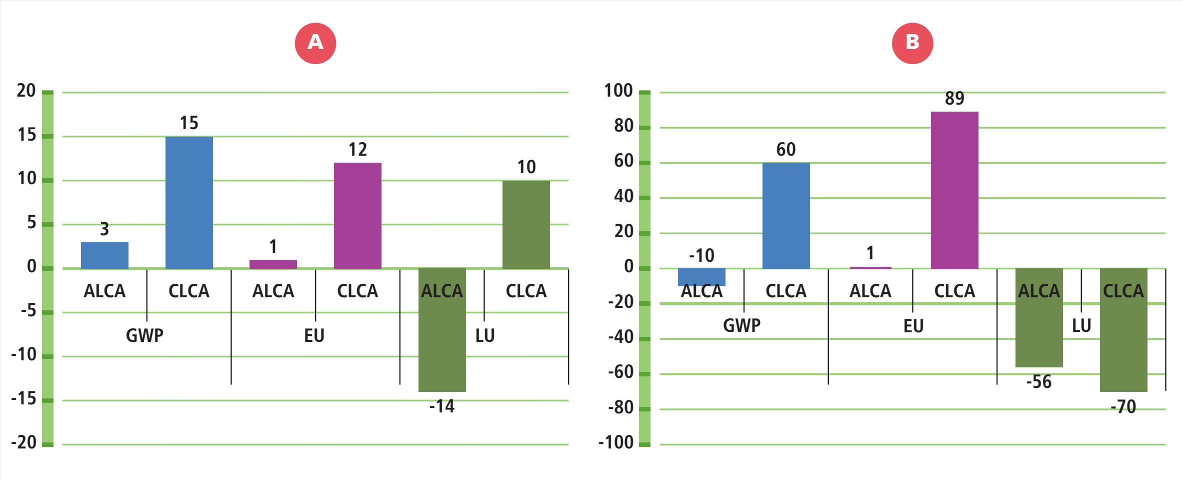
**Difference in the calculated impact of feed choice by ALCA and CLCA in pigs**

The complexity involved in assessing environmental impacts can lead to divergent results between ALCA and CLCA. Van Zanten *et al.* (2018) assessed the potential of replacing soybean meal (SBM) with more circular feed sources such as rapeseed meal (Fig. A) or residuals-fed larvae meal (Fig. B).

As these figures show, differences arise between the ALCA and the CLCA with regards to land use, energy use and global warming potential. Overall, the ALCA had a lower percentage change than the CLCA for these three environmental parameters. Impacts are substantially higher for CLCA than for ALCA, which indicates that the system expansion results in clear environmental trade-offs. For land use, this is most obvious when soybean meal is replaced by rapeseed meal, amounting to a 24 percent shift in impact from land freeing to using land. Similarly, replacing soybean meal with residuals-fed larvae meal resulted in a 70 percent shift in global warming potential and 88 percent shift in energy use. As this example makes clear, caution should be applied when developing policies based on ALCA results.

*Note:* Percentage change in the environmental footprint resulting from the ALCA and CLCA approaches, by replacing soybean meal with rapeseed meal (Fig. A) and with residuals-fed larvae meal (Fig. B) in the diet of finishing pigs. ALCA = attributional life cycle assessment (LCA); CLCA = consequential LCA; GWP = global warming potential; EU = energy use; LU = land use.

*Source:* Authors' own elaboration.




um, system dynamic optimization or multifunction weighted models to assess outcomes at subsystem, regional, national or global modelled scales (Reilly and Willenbockel, 2010). However, as a result of the complex and multifaceted structure of most food system models, it is difficult to characterize the intermediary changes resulting in the desired outcome. Consequently, these models use baseline comparisons, often in the form of the current food system, to explore how the modelled changes alter the footprint of the food system (Reilly and Willenbockel, 2010). Exploring circular livestock systems through food system models requires significant biophysical and economic data to precisely model the interlinkages that are impacted as a result of food system redesign. This data requirement has constrained circular food models in their ability to explore the bioeconomy. Gatto *et al.* (2024) have investigated these dynamics with the help of an economic model, but more work is needed to explore the bioeconomy of circular livestock systems.

## 2.2 RECOMMENDATIONS AND CONCLUSION

Circularity can be measured by means of different indicators, each emphasizing a particular metric, yet all contributing to assess the role of livestock in the bioeconomy. To date, there is no single circularity framework model that simultaneously examines target-based indicators, practice-based indicators, result-based indicators and outcome-based indicators. Assessing practice-based and/or result-based indicators without outcome-based indicators raises the risk that potential negative or positive effects associated with a food system will be overlooked. Although outcome-based indicators like NUE, LCA and integrated food system models are more complex and time-consuming to generate, they provide a more comprehensive overview of the sustainability of food systems compared to other indicators (target-based, practice-based, results-based).

Life cycle assessments can be used to evaluate the environmental impact of livestock production. Attributional life cycle assessment, which use fixed-impact intensities, are appropriate when production practices do not significantly affect elements beyond system boundaries. In contrast, CLCAs can provide additional insights when changes in production have broader systemic effects. Fixed-impact assessments, such as ALCAs, are particularly useful for identifying environmental hotspots, in which targeted technologies and management practices can be applied to reduce negative environmental impacts. Attributional life cycle assessments and CLCAs play a vital role in assisting farmers and industry to make decisions that improve the sustainability of their product(s) in the short term. Marked by an increased use of LCB, the evolution towards circular livestock production systems will call for redesigning the current livestock system over the long run. This implies large-scale changes that lead to cascading effects and require careful consideration of co-product linkages and suitability at a time of growing resource scarcity.

Integrated models such as food system models can capture this complexity. Such an approach does not focus on efficiency measures, i.e. land use per unit commodity, but on the total impact of the whole food system, including all the underlying interlinkages, mass and nutrient flows and their total impact in relation to livestock and human diets (Manzano *et al.*, 2023). While the examples given in this chapter were European-centred, the science of metricizing the role of livestock in circular food systems should be explored in a location-specific manner better to reflect the intricacies present in those systems. Future research on this subject should also focus on the circular livestock systems of the Global South to improve the knowledge and representation of these regions.

Policymakers should thus combine long-term strategies drawing on food-system modelling studies that embrace the food system's complexity with short-term strategies that can be implemented directly, based on fixed-impact assessments that represent the current situation. Choosing the correct methodological approach is essential to avoid confusion, while ensuring effective policy design and communication (Van Zanten *et al.*, 2022).

BOX 5
**Circular food systems**

Circular food systems (CiFoS) (Van Zanten *et al.*, 2023) is an example of a biophysical food system. It is a biophysical optimization model used to explore the effects of adopting different circularity scenarios at different scales (regional to global). It accounts for the potential use of natural processes and cycles to ensure that residuals and co-products from one process are the inputs to another process. For example, human-inedible co-products can be used as fertilizers for crops or as feed for livestock. Circular food systems facilitates food system redesign by minimizing defined environmental impacts (e.g. land use of GHG emissions), while delivering dietary scenarios that meet human nutritional requirements. This approach considers potential constraints on macro- and micronutrients, protein and energy intake per capita.

The model selects a combination of food items from plants, livestock, captured fish and aquaculture that minimized land use. The results show that agricultural land use could be reduced by 71 percent and GHG emissions by 29 percent per capita, while still having a healthy and self-sufficient EU and UK food system (Van Zanten *et al.*, 2023). These cuts are due to fewer waste streams, the reallocation of resources and a reduction in animal numbers. In Europe, such a transition requires a change in the ratio of animal-to-plant proteins in the human diet from the current 60:40 to 40:60. This will result in a 51 percent reduction in the daily animal protein intake per person, from 49 g to 24 g. The consumption of most animal proteins will be reduced, and mainly associated with red meat and chicken. In this scenario, the recommended intake of macro- and micronutrients is met, and the diet is nutritionally balanced. Such a dietary shift also requires a change in crop and livestock production systems. Crop production changes from predominantly grains and oil crops to more diverse cropping systems, with more vegetables and pulses. Livestock production systems will largely decrease, especially for suckler beef, broilers and pigs, with only small changes in dairy, laying hens and fish (Van Zanten *et al.*, 2023). A more comprehensive overview of a food system's impact can be gained from other holistic factors such as economic suitability or energy use. (Koppelmäki, Helenius and Schulte, 2021; Latka *et al.*, 2022; Burg *et al.*, 2023).

## Chapter 3

# Sources of co-products for feed and other applications

The potential of co-products for use in feed depends on their nutritional value for livestock and their potential incorporation rates in livestock diets. The nutritional value of a co-product varies depending on the region and on the manufacturing process of the main product. A co-product's nutritional value is generally compared to the nutritional value of the feed ingredient it is intended to replace. Concentrations of crude protein, digestible carbohydrates, minerals and vitamins are important elements that determine the nutritional value of co-products. The presence of indigestible fibres and antinutritional factors (ANFs) can influence the nutritional value of co-products. Ideally, digestibility coefficients for all the nutrients would be available in nutritional tables, such as the Dutch table (Spek and Blok, eds 2018) or the National Institute for Agricultural Research (Institut national de la recherche agronomique, INRA) table (Sauvant, Perez and Tran, 2022) or the INRAE–CIRAD–AFZ Feed tables (feedtables.com). However, in most cases, digestibility coefficients are unavailable, making it necessary to develop alternative approaches:

1. One approach is to estimate the relative energy value of the co-product (Blas Beorlegui *et al.*, 2021). This approach uses the co-efficient of digestibility of a feed ingredient that is most like the new co-product being evaluated. Fats and nutrient digestibility coefficients of similar feed ingredients that are most relevant to the new co-products are also considered.
2. Another option relevant to PBPs is to use equations to calculate digestibility based on the chemical composition of the co-product.

Once the losses resulting from indigestibility have been accounted for, the estimation of metabolizable energy mostly depends on the co-product's protein and fibre content, while net energy depends on its protein, fat, starch and fibre content (Appendix 1).

As proteins are made up of amino acids that determine protein quality, it is important to assess the digestibility of each amino acid present in the co-product's proteins. In the case of monogastric animals, the procedure used to evaluate a co-product consists of estimating the total amino acid composition and calculating the ileal digestibility by applying the protein table values adjusted to the protein level of the co-product under evaluation.

Phosphorus (P) is the third most expensive nutrient in the diet (Satter *et al.*, 2005; Moe, 2008), which makes it necessary to consider the digestibility of P in the co-product, usually using tables that outline P availability in similar products.

Sampling is an important aspect of properly evaluating the nutritional characteristics of a co-product. The use of recognized international sampling methods ensures a standardized administrative and technical approach and facilitates the interpretation of analytical results. FAO and the International Feed Industry Federation (IFIF) (2020) provide a detailed review of acceptable sampling methods.

### 3.1 PLANT-BASED PRODUCTS OPPORTUNITY IN THE CIRCULAR BIOECONOMY

Several sources of PBPs are already fed to livestock. Food processing, oil extraction, alcohol production and food loss all give rise to PBPs. In some instances, PBPs are produced at the site of primary production, as in the case of straw generation during grain harvest. In others, they are produced during the processing, as peels from tubers. The increased PBPs use can make livestock production systems more sustainable and reduce the food–feed competition for land. The use of PBPs may be considered to offset the GHG emissions associated with the dietary component that they replace, while avoiding the additional GHG emissions that would be incurred if they were disposed of in a landfill or through combustion. However, the PBPs composition can be highly variable, making it challenging to formulate diets that meet the nutritional needs of livestock. Furthermore, some PBPs may contain toxins or ANFs that restrict or limit their inclusion in livestock diets. Care must be taken to ensure that including PBPs in the diet of livestock does not adversely impact growth, productivity or health in a manner that would reduce sustainability and increase the environmental footprint of livestock production systems. In the following section, several of the main PBPs used as feed ingredients for livestock are outlined and classified according to the production process of the main product (fermentation, crop residues, industrial processes, food loss). A table providing information on their nutritional value and use in feed is included in Appendix 2. Additional examples of potential co-products for use in feed are provided in Appendix 3.

### 3.1.1 Co-products from fermentation processes

Fermentation processes are used to produce foods, drinks or biochemicals, such as ethanol. For example, cereal grains can be fermented to produce beer, distilled spirits or bioethanol. Distillers' grains that are co-produced may be fed to livestock in either a wet or dry form (Zijlstra, 2021). Fermentation may also be used to produce biochemicals (e.g. vitamins, carotenoids, enzymes), sometimes involving the use of genetically modified microorganisms. Some co-products derived from fermentation processes are described in what follows.

**Spent brewer's grain** is the most abundant co-product generated by the beer brewing industry, accounting for up to 85 percent of the total co-products, mainly used as cattle feed. There is an increasing interest in using protein hydrolysis to produce bioactive peptides from spent brewer's grain for additional food and nutraceutical applications (Lynch, Steffen and Arendt, 2016; Connolly *et al.*, 2017; Shen *et al.*, 2019).

**Brewer's yeast** (*Saccharomyces* spp., *S. bayanus*, *S. cariocanus*, *S. cerevisiae*, *S. kudriavzevii* and *S. mikatae*) biomass is the second major co-product arising from the brewing process (Kurtzman and Robnett, 2003).

Both spent brewer's grain and yeast can be dried to improve their storage stability and ease transport to where it is consumed. Dried yeasts are often included in diets for pigs and ruminants, owing to their high level of protein and probiotic properties (Ferreira *et al.*, 2010; Huige, 2020).

**Distillers' grain and solubles** are co-products of ethanol production, derived from the fermentation of grains such as corn, sorghum, wheat, barley, oats or rice (Bothast and Schlicher, 2005). Distiller's grains with solubles can be fed to livestock either wet or dry. Depending on the technology used for production, co-products from ethanol production can consist of either condensed distiller's solubles (35–40 percent solids), wet distiller's grains (20–30 percent solids) or thin stillage (5–10 percent solids) (Mohammadi Shad, Venkitasamy, and Wen, 2021). The nutritional value of grain distillers varies depending on the processing plant, the fermentation process and grain type. In dried distillers' grains with solubles, oil is also a co-product, although levels have declined as a result of its increased extraction for use in biodiesel production. One of the benefits of dried distillers' grain with solubles in the diet of ruminants is that it can result in a reduction of enteric $CH_4$ emissions, if the oil content of this co-product is retained (Pecka-Kielb *et al.*, 2017).

### 3.1.2 Crop residues

Straw and stovers are the main crop residues of cereals (rice, wheat, barley, rye, triticale, oats, corn, sorghum) and legumes (soybeans, lentils, beans, peas).

**Straw** is available in large quantities, typically accounting for more than half of the crop's harvestable vegetation. Depending on harvesting practices, in some regions straws are left on the ground to contribute to soil organic matter, while in others they are burned, thereby lowering air quality and losing nutrients. Their low digestibility makes straws largely unsuitable for monogastric livestock and, as a result, they are mostly fed to ruminants. Finally, they can also be used as bedding for livestock and as a rich source of fibre for other uses.

Straw supports the seed head of cereals and is therefore very fibrous. The composition of straw depends on the leaf-to-stem ratio, the diameter of the stem and the height of the plant. Most of the nutrients in cereal straws (including protein and minerals) are bound to the cell wall. Straws have an average neutral detergent fibre (NDF) content of 70 percent, consisting mainly of cellulose, hemicellulose and lignin. Rice straw contains less lignin than other straw but has a higher silica content (Heuzé *et al*., 2015a). The crude protein content of straw is very low (<5 percent) and indigestible. Straw is also markedly deficient in most minerals – except for potassium (K), chlorine and iron – and vitamins. Because of its low nutritional value, straw is mainly incorporated at high rates in maintenance rations for ruminants (Blas Beorlegui *et al*., 2021).

**Corn stover** is a fibrous feed ingredient, usually of better nutritional quality than other cereal straws, but its high-water content can make it difficult to preserve.

Straws can be physically and/or chemically treated (e.g. with sodium hydroxide, ammonia [$NH_3$] or urea) to improve palatability, intake and digestibility. Grinding and pressure cooking straw can improve its digestibility (Sarnklong *et al*., 2010), but are often too expensive to be commercially viable. Grinding and subsequent pelleting of straw is a practical method designed to increase the intake and facilitate handling. A classic treatment with sodium hydroxide is the Beckmann method, recommended by FAO (2008) because of its applicability on a small or large scale. The scale of operation and the degree of mechanization of the Beckmann treatment varies widely. In this process, straw is immersed in a 1.5 percent solution of sodium hydroxide for 18 to 20 hours (FAO, 2018a). This process is intended to disrupt the crystalline structure of the cellulose, improve its hydration capacity, and hydrolyse linkages between phenolic compounds and hemicellulose. The success of the process depends on several factors, notably the type and quality of the straw, the amount and form of sodium hydroxide addition, and the applied pressure and temperature. The treatment results in a 30–35 percent improvement of the energy value of the straw by increasing the NDF degradability (Blas Beorlegui *et al*., 2021). Urea has been used to treat rice straw and is suitable for both small- and large-scale livestock production stakeholders (Aquino *et al.*, 2020). The main function of urea is to increase the non-protein N content and enhance the fermentation of straw in the rumen. Urea or $NH_3$ are best when used in combination with molasses (urea–molasses solution) to treat straw with a 30 percent moisture content. Rice straw can be effectively treated with urea using concentrations ranging from 1 to 5 percent w/w (Aquino *et al.*, 2020).

### 3.1.3 Co-products from industrial processes

Various biomass industrial processes lead to the production of co-products. Some of these co-products are described in this section.

Soybean (*Glycine max*) oil extraction produces **soybean meal (SBM)** as the major co-product, which is the most globally used protein source in livestock diets, with 98 percent of production used as a feed ingredient. A voluntary certification system to ensure sustainable production was developed by the Roundtable on Responsible Soy Association. In 2021, 246 million tonnes of SBM were produced globally, with China, the United States of America, Brazil and Argentina being the largest producers. After oil extraction, about 80 percent of the beans remain as SBM. Soybean meal is heated during production to inactivate trypsin inhibitors that would adversely impact protein digestion. Lower in fibre than most other oilseed meals, it has an average crude protein content of 44–48 percent. Soybean meal is considered to have the highest biological value among plant-based protein sources and is particularly rich in lysine (Garcia *et al.*, 1998). **Soybean hulls** may also be removed prior to oil extraction and added to the diets of ruminants as a readily digestible source of fibre. Cultivation of soybeans continues to expand globally, and it is commonly used in crop rotations with cereal grains.

**Peanut meal** is a co-product of oil extraction from partially decorticated peanuts (*Arachis hypogaea*). It is rich in highly digestible protein but is deficient in methionine, lysine and tryptophan. Various types of peanuts are available on the global market and they differ depending on their geographical origin (India, China, West Africa), the oil extraction process used (solvent, expeller) and the extent of decortication (Blas Beorlegui *et al*., 2021). High in protein and oil and low in fibre, peanut meal largely lacks ANFs. It is often the default protein in regions where SBM is too expensive or not available. Peanut meal can be contaminated with aflatoxins. However, in recent years this issue has almost been eliminated through improved production practices.

**Sunflower cake** is obtained by squeezing oil from sunflower (*Helianthus annuus*) seed, and is a valuable high protein and energy supplement. **Sunflower meal** is obtained after solvent extraction of cake. Although lignin content can be high, it does not contain toxins or other ANFs. Nevertheless, it is lysine-deficient for monogastric animals (Heuzé *et al*., 2019).

**Rapeseed meal/cake/expeller** (canola meal/cake/expeller in Australia, Canada, the United States of America and some other countries) is one of the co-products obtained by the extraction of edible oil from rapeseed (*Brassica napus* L., *Brassica rapa* L., *Brassica juncea* L.). Worldwide production of rapeseed meal is second only to SBM (USDA, 2016). The use of rapeseed meal in the diets of both pigs and cattle has increased because of the development of low erucic and glucosinolate varieties by Canadian and European plant breeders. To be used as feed, the varieties of rapeseed must be categorized as "00", indicating that it has low erucic acid and glucosinolate content. These rapeseed varieties are now the main ones grown across the world. Oil-rich rapeseed meals, obtained by mechanical pressing (expeller or cake) may also be used in feed. Processing temperature is important to denature the remaining glucosinolates, but high temperature may also denature proteins and reduce P availability. In ruminants, the rumen bypass protein obtained with heat treatment may increase the flow of amino acids to the small intestine. In general, cold-pressed cake (60 percent) is higher in oil (5–20 percent and more) and in glucosinolates than solvent-extracted meals (100 °C). Rapeseed meal also contains tannins that bind protein, as well as a higher amount of crude fibre – 15 percent of the dry matter (DM) – than SBM, which may reduce its inclusion rate in monogastric diets. Furthermore, rapeseed meal is generally considered low in lysine and it can be high in lignin.

**Palm** (*Aceraceae* spp.) trees can be harvested for 20 to 25 years and annually yield 8 to 10 fruit branches, each weighing 15–25 kg. A voluntary certification system developed to ensure sustainable production by the Roundtable on Sustainable Palm Oil was estimated to reduce GHG emissions from palm oil production by 35 percent (Schmidt and De Rosa, 2020; Akinyele, Olaniyi and Arotupin, 2011). That said, palm plantations can still negatively impact biodiversity. After press extraction of the fruit, the co-product (the mesocarp of oil palm fruit) may be further subject to solvent extraction. Oil represents about 45 percent of the kernel, with the derived **palm kernel meal** suitable as a feed ingredient, despite having lower energy and protein levels than other oilseed meals (e.g. soybean, rapeseed or sunflower). Indeed, its protein content is inferior at 20 percent, and it has highly lignified fibre and low solubility as a result of its high galactomannan content. In addition, the fibre content is variable, making its nutritional value heterogeneous. **Palm kernel cake** contains more fat than solvent-extracted meals and is therefore more energy-rich. Palm kernel cake contains ANFs (0.40 percent tannic acid, 6.62 mg/g phytin-bound P, 23-49 mg/g phytic acid and 5.13 mg/g oxalate), which negatively affects nutritional quality (Akinyele *et al.*, 2011). Fermentation or enzymatic hydrolysis (by mannanase) have been used to improve the nutritional value of palm kernel cake for monogastric animals. Bioactive lipids are also present (e.g. lauric acid), which may have positive effects on livestock (antimicrobial and probiotic activity), but the protein present in palm kernel cake is deficient in lysine and sulphur containing amino acids. Oil palm processing also yields numerous other co-products, including **empty fruit branches**, **nut shells**, **palm press fibre** and **palm oil mill effluent** (Heuzé *et al*., 2016b).

**Linseed cake** is a co-product of pressing linseed (*Linum usitatissimum*). Although rich in protein, linseed cake is low in lysine. The oil is particularly high in omega-3 fatty acids, which, when incorporated into milk and meat, can improve their health properties (Shingfield *et al.*, 2011). Linseed cake can contain ANFs such as cyanogenic glucosides (normally inactivated by thermal or chemical treatment), vitamin B6 antagonists and mucins (Doreau and Ferlay, 2015).

**Cottonseed** (*Gossypium* spp.) is crushed, with 80 percent of it processed in the United States of America by expander-solvent extraction. Globally, cottonseed is still being processed using a variety of extraction procedures (O'Brien *et al.*, 2005). **Cottonseed meal**, the co-product of oil extraction, is mostly used to feed ruminants, which are more tolerant to the gossypol toxin than monogastric animals. It can be a good source of protein for monogastric animals, provided that its high-fibre content and the presence of gossypol are considered during diet formulation (Tanksley, 1990; Chiba, 2000). Cottonseed meal is also used as a fertilizer (Heuzé *et al*., 2019). Incorporating processed cottonseed co-products, such as cottonseed meal and high oil cottonseed meal, in lamb diets enhances carcass traits and increases the levels of beneficial fatty acids in meat. Gossypol has been shown not to affect rumen methanogenesis (Lima *et al.*, 2014).

**Olive pomace**, the main co-product arising in the process of extracting oil from olives (*Olea* spp.), may be dried to generate a product that is high in oil once the pits are separated. Olive pomace can either be marketed as such or partly defatted. To facilitate handling, it can be pelletized. Olive pomace is high in lignin and the protein may have reduced biological value if it is tightly bound to plant cell wall carbohydrates (Blas Beorlegui *et al*., 2021; Berbel *et al.*, 2018). Whole or partially defatted olive pomace are feed ingredients mainly used for their significant oil content. Tzamaloukas, Neofytou and Simitzis (2021) found that olive pomace increases the levels of monounsaturated fatty acids and decreases saturated fatty acids in milk and meat from ruminants. The highly lignified fibre of the other olive co-products limits their use in monogastric animals. In periods of feed scarcity, it can be included in ewe or goat diets at a high level (70 percent) to meet maintenance requirements (Heuzé *et al*., 2015b; Bionda *et al.*, 2022).

**Glycerin** makes up approximately 10 percent of the total volume of biodiesel and can be used as a feed ingredient (Kholif, 2019). The glycerol it contains can help livestock to synthesize glucose and is an important energy source for cellular metabolism. In ruminants, glycerol is fermented in the rumen to produce propionic and butyric acids. Parsons, Shelor and Drouillard (2009) noted that the inclusion at moderate levels of glycerin in the diet can improve feed conversion in growing or finishing ruminants.

**Sugarcane** (*Saccharum officinarum)* can be processed into raw or white sugar crystals as a sweetener of food and beverages or it can be turned into several forms of molasses for use in the production of other products such as rum and beer or used as a feed ingredient. Pressed sugarcane (**bagasse**), molasses and calcium oxide or press mud are the main co-products of sugar production (Gudoshnikov, Jolly and Spence, 2004; Raza *et al.*, 2021). Sugarcane bagasse is the main co-product of the sugarcane industry; it contains 60 to 70 percent carbohydrate, but its low digestibility and high lignin content makes it most suitable as a feed for ruminants (Shelke *et al.*, 2009; Atta Elmnan and Ismeal, 2019). Bagasse can be dried or ensiled before being used. Attempts to improve the nutritive value of sugarcane bagasse have focused on technologies that break the linkages between hemicellulose and lignin. Several mechanical, chemical and biological processes have been explored, and some combined biological and chemical treatments have been adopted (Shelke *et al.*, 2009; Lunsin *et al.*, 2018). However, because of high costs, most of these approaches are not economically viable. As a result, sugarcane bagasse is primarily used as a fuel source in sugar production, while press mud is typically disposed of by spreading it on cropland. Nevertheless, sugarcane and its co-products are widely used across various industries, including food, chemicals and thermal power generation (Akbar and Ali, 2017; Srivastava, 2020). Sugarcane molasses have a wide range of applications, including in human health and as a feed ingredient. Distilleries and pharmaceutical industries are also end-users of this co-product. Demand for molasses as a feed ingredient is on the rise, while its high concentrations in cane juice make it a valuable substrate for distilleries and the fermentation industry (Rodríguez and Preston, 1997; Mordenti *et al.*, 2021).

A co-product of molasses fermentation, **sugarcane vinasse** is a dark red liquid with an acidic pH around 4.5, high viscosity and about 65 percent DM. In cattle feed, vinasses can be included in the diet at up to 10–15 percent of DM and up to 30 percent of DM in growing pigs (Ramos-Hernández *et al.*, 2021). High in organic matter, N, P, potassium (K), sulphur and calcium (Ca), sugarcane vinasse can be used as a substitute for chemical fertilizer in crop production (Joshi *et al.*, 1994). **Sugarcane juice**, extracted by squeezing sugarcane stalks through a juice extractor, is high in fibre, soluble carbohydrates, vitamins, minerals and phytochemicals. It also has a low glycemic index, making it suitable for diabetics, and is valued for its high content of antioxidants. Sugarcane juice is also an energy-rich feed ingredient that has been included in the diets of both cattle (Sanchez and Preston, 1980) and pigs (Xuan Dung *et al.*, 2010).

**Sugar beets** (*Beta vulgaris*) produce about 130 million tonnes of sugar annually, i.e. about 35 percent of the world's sugar (Harveson, 2013). **Sugar beet pulp** is obtained as a co-product in the extraction process of sugar. The pressed sugar beet pulp has a DM content of 18–23 percent w/w and contains up to 75 percent w/w of carbohydrates on a DM basis. Sugar beet pulp is relatively low in crude protein (8 percent) and high in total digestible nutrients (72 percent) (Berlowska *et al.*, 2018). It is mainly used as a feed ingredient for dairy cows. It has been landfilled in regions with no livestock (Kühnel, Schols and Gruppen, 2011). Sugar beet pulp can be used effectively as a supplement for gestating or lactating cows, as a bulking ingredient in rations or as a replacement for roughage in finishing diets for ruminants (e.g. beef, sheep).

**Wheat** (*Triticum aestivum*) contains starch, protein and fibre and is an important food and feed source (Yang and Shen, 2018). After the extraction of starch, 25–40 percent of the original wheat kernel remains as a co-product and can be used as a feed ingredient. Wheat that fails to meet the criteria for human consumption can also be fed to livestock. Whereas co-products associated with the wheat germ can be fed to all livestock, fibrous co-products such as **wheat bran** are more suitable for ruminants. Wheat bran is a co-product of dry milling wheat into flour and is commonly used in breakfast cereals for humans. The fibre-to-starch ratio in wheat bran can vary substantially depending on the milling process. Worldwide production is estimated at 45–90 million tonnes. Fibre is the main constraint to using wheat bran in feed, particularly in diets for monogastric animals. Some of the reduction in the diet's energy content linked to the addition of wheat bran may be compensated for through an increase in feed intake (Heuzé *et al.*, 2015c). **Wheat middlings** are also produced during the milling process and consist of a mixture of wheat bran, endosperm and germ. Wheat middlings are lower in fibre and higher in starch content than wheat bran (Heuzé *et al.*, 2015c). The germ represents about 2.5–3.8 percent of the total seed weight and is rich in bioactive compounds (Brandolini and Hidalgo, 2012). **Wheat gluten feed** is a blended co-product of the milling industry. Its components mainly come from the germ and endosperm of the kernel. It is fed either in pelletized or powdered form. The low molecular weight proteins in wheat gluten feed provide viscosity, elasticity and cohesion to manufactured feeds. Enzymatic hydrolysis of gluten proteins has also been shown to improve antioxidant and anti-inflammatory status in the guts of pigs and poultry.

**Corn** (*Zea mays*) milling produces starch and oil along with multiple co-products, known as **corn gluten feed** (fed both wet or dry), **corn gluten meal**, **corn germ meal** and **corn steep liquor**. Corn gluten feed consists of corn bran, corn steep liquor and germ meal (Hoffman and Baker, 2011). Corn gluten feed is widely used in feeds for ruminants, poultry and pigs (Li *et al.*, 2012) as a high energy and protein feed ingredient. Unlike the name suggests, corn gluten feed does not contain the common allergenic gluten protein (gliadin) but rather zein and glutelin. Corn gluten meal is used as a source of pigments for livestock species and as an organic fertilizer and natural herbicide. Corn germ meal is the co-product of oil extraction from the germ and is a useful carrier for liquid ingredients. Its nutrient content can vary widely, depending on the processing. Wet milled corn germ is similar in composition to corn gluten feed, whereas dry milled corn germ has a nutrient profile that resembles more closely corn bran or hominy feed (CRA, 2006; Heuzé *et al*., 2015d).

**Potatoes** (*Solanum tuberosum*) and potato co-products are also used in feed for livestock. **Raw, uncooked potatoes** can be fed directly to ruminants but, for pigs, **cooked potatoes** are used as cooking gelatinizes starch and increases their digestibility (Potatoworld, 2021). On a DM basis, potatoes contain 10–12 percent crude protein with a high biological value (70–90 percent) and a high lysine content (Hussain *et al.*, 2021). **Potato peels** can be used in feed for lactating cows and beef cattle. After drying, potato peels can be mixed with coagulated **potato proteins** to formulate a more balanced supplement for livestock (Haverkort, 2023). Potato proteins are concentrates that can be extracted directly from the tuber or more commonly from the potato juice produced during the extraction of starch. The juice is acidified and heated to coagulate the proteins, precipitated, separated and dried. **Potato pulp** remains after rasped tubers have been soaked in cold water and exuded, and once protein water solubles have been extracted (Gumul *et al.*, 2020). After potatoes have been sliced, chipped or diced for cold water extraction, **potato puree** is recovered. The remaining starch is washed with hot water to gelatinize it and increase digestibility. The product can be concentrated (17–23 percent water) for liquid feedings to pigs and dried for ruminants (Crawshaw, 2004).

**Rice** (*Oryza sativa*) milling produces the **rice husk** (20–30 percent) and **rice bran** (10 percent) as major co-products. Rice bran, often a mixture of co-products, is a valuable feed ingredient for livestock. However, it may become rancid during storage because of its high oil content, a risk that can be avoided if defatted rice bran is used as feed (Heuzé *et al.*, 2015e).

BOX 6

**Case study: The use of plant-based products in livestock feed in Paraguay**

Paraguay has 6.1 million people and 17.8 million livestock – cattle, sheep, horses, pigs, goats and poultry – as of August 2024 (MDS, 2024). According to the National Development Plan 2030, the country sees its greatest opportunity for development in positioning itself as a global platform for food production. Paraguay is the 6th largest producer of soybean and its 4th global exporter (Calzada and Sigaudo, 2019; UNDP, 2024). In addition, in the last decade, it was ranked in the top 10 of the world's meat exporting countries (USDA Foreign Agricultural Service, 2024). The cost of feed inputs for the meat and dairy sectors constitutes 70 percent of the total production cost. Soybean is Paraguay's main crop, but wheat, sunflower, canola and their co-products also contribute significantly to the agricultural sector. Conserved forages (hay, silage and haylage), non-cereal crop stover and other sources of bulky or high-fibre plant biomass are also used as feed. Co-products, including citrus pulp, coconut pulp, sugarcane bagasse, cassava bagasse, cotton hulls, soybean hulls, rice hulls and sesame hulls, are also used in feed. In addition, concentrate formulations use cotton meal, soybean meal, sunflower meal, canola meal, coconut almond meal, peanut meal, corn gluten meal, molasses, wheat bran, rice bran, whole and split soybean seed.

Feed regulations, including those governing the use of co-products that may be raw materials or supplements, are based on standards established by the Animal Health Service (National Service of Quality and Animal Health, SENACSA).

**Highlights**

- In Paraguay, 10.2 million tonnes of grain are produced and over 5 million tonnes of soybean are exported, equivalent to USD 1 963 million every year:
  - total production 2023/2024
  - soybean 6 493 929 tonnes
  - wheat 348 706 tonnes
  - corn 3 301 377 tonnes
- Livestock represents 12.1 percent of Paraguay's gross domestic product (GDP). Paraguay has more than 150 000 cattle herds with 13.9 million heads of cattle, grazing on about 26 000 000 hectares of land.
- Cattle ranching supports 12.1 percent of the workforce, making it vital for the economy and people's livelihoods.

### 3.1.4 Food loss and processing co-products

Food loss from supermarkets, food stores, restaurants and households along with co-products generated during the processing of fruits and vegetables are often rich in nutrients and bioactive compounds that can provide nutritional and health benefits to livestock (Kasapidou, Sossidou and Mitlianga, 2015).

**Vegetable co-products** are the secondary products that are often discarded or fail to make the quality grade for human consumption during food processing. Up to one-third of vegetables can fall into this category. Vegetable co-products also include seed coats from the processing of grains and oilseeds, peelings from tubers, gourds and other root crops, as well as stalks and plant parts that are not directly consumed as food.

**Fruit co-products** are one of the principal sources of municipal solid waste, partly because of their short shelf-life. Fruit peels or rinds are commonly discarded during manufacturing and not consumed. For example, grapefruit, banana, orange and melon are rich in carbohydrates and, in addition to being used as feed ingredients, they can serve as substrates for anaerobic fermentation, the production of insect protein (e.g. black soldier fly [BSF], *Hermetia illucens*) or biofuels. Rich in nutrients, **fruit seeds** are used as feed ingredients. Care must be taken to ensure that the seeds do not contain secondary toxins or that the toxins are inactivated during secondary processing. **Fruit pomace** is what remains after juice extraction, which may include seeds, skin, pulps and stems. It is often rich in dietary fibre, antioxidants and phenolic compounds. Fruit pomace is commonly included in ruminant diets owing to its high fibre content. Examples of pomace sources include apples, tomatoes, apricots, grapes, mangos, cucumbers, oranges and lemons. In 2022, 158.2 million tonnes of citrus (*Citrus reticulata*) were produced globally, with China, Brazil, the United States of America and the European Union being the largest producers. Citruses are a valuable source of fibre, flavonoids, polyphenols, sugars, carotenoids, ascorbic acid, essential oils and vitamins (Suri *et al.*, 2022). An estimated 50–70 percent of world citrus production is juiced, generating ~96 million tonnes of citrus pulp annually for use as feed ingredients. Citrus pulp can be fed fresh as silage or dehydrated, making it more suitable for trade. Citrus pulp can constitute 30–40 percent of the diet DM (Bampidis and Robinson, 2006). Barriers to the use of fresh citrus pulp in feed include inconsistent seasonal supply, incompatible growing conditions (i.e. tropical vs subtropical), costs of transportation from the processing site to the feeding site as well as rapid spoilage. Ensiling or dehydration (90 percent DM) can reduce spoilage and lower transport costs.

Economic low-energy solar and air-based drying technologies reduce the reliance on non-renewable fuels for drying (Badaoui, Djebli and Hanini, 2022; Suri *et al.*, 2022). In addition, global, regional and national training strategies can be developed and implemented to encourage producers to use citrus pulp as feed ingredients.

### 3.1.5 Disadvantages and challenges

Animal diets formulated with a higher proportion of diverse co-products and other human-inedible ingredients are usually low in starch and high in fibres with variable concentrations of protein, fat and phytate. Because of their high-fibre content, co-products are by and large more suitable for inclusion in ruminant diets. Different processing methods can result in a high variability in the nutrient composition of the co-products. The heterogeneity of co-products and food residuals poses challenges as their nutrient composition can vary considerably both within and between batches, making it difficult to formulate balanced diets that meet livestock requirements. For example, screenings from grains and oilseeds are often marketed based on bulk density, which offers limited insight into their nutritional value. Consequently, the nutrient composition of these products must be measured regularly, with diets reformulated accordingly (Ominski *et al.*, 2021). Co-products with an elevated moisture level (above 12–14 percent) may be prone to microbial degradation, leading to nutrient loss and the potential formation of poisonous substances like mycotoxins (Magan and Aldred, 2007; Neme and Mohammed, 2017). In liquid co-products, facultative anaerobes like yeasts may develop and rapidly degrade DM (Van Donselaar, 2015).

Methodologies designed to manage risks should factor in sustainability implications. For example, drying feed ingredients typically relies on fossil fuels, thereby increasing the food system's GHG emissions. Ensiling and other such preservation methods can also be used, but these do not appreciably lower the moisture content of the feed ingredient and often limit how far it can be economically transported. Many co-products are not available all year round or their quantities are inadequate for use at scale, making it necessary to frequently reformulate diets. Some co-products must be fed immediately or preserved through drying, ensiling or chemical treatments. This is particularly important for co-products with high moisture or lipid content as spoilage and oxidative rancidity can become an issue (Salami *et al.*, 2019).

Plants synthesize various plant secondary metabolites (PSMs) that are often involved in ecological interactions between the plant and its environment. Some PSMs can be neutral or beneficial for livestock, while others, such as ANFs, are nutritionally deleterious. These ANFs make no positive contribution to the nutritional value of the diet and frequently depress it. Some of these ANFs are proteins like trypsin inhibitors. However, the most numerous are low-molecular-weight phytochemicals, such as polyphenols (tannins, gossypol, chlorogenic acid), glycosides (glucosinolates, saponins, alkaloids, estrogens, cyanogenic substances), oligosaccharides (β-glucans, xylans) and organic acids (phytic acid, oxalic acid) (Mateos *et al.*, 2019). The effects of ANFs can vary from hardly noticeable (subclinical) to overtly toxic or poisonous (Pusztai, Bardoez and Martin-Cabrejas, 2004). Several of the ANFs are proteins and thus sensitive to heat, which means that heat treatment can reduce or eliminate their deleterious effects. However, as some ANFs are heat-resistant, it is necessary to reduce their toxicity through other methods. Lastly, co-products containing ANFs whose deleterious effects cannot be effectively reduced or inhibited by any method should be used sparingly and directed towards livestock that can tolerate them. Many PSMs have potential beneficial effects, such as essential oils from aromatic herbs as well as carotenoids and xanthophylls (e.g. lutein or zeaxanthin) present in corn gluten meal and other co-products. Moreover, many polyphenols, including flavonoids, are well known for their antioxidant properties. Their use is becoming increasingly popular for addressing the nutritional needs of livestock that are exposed to oxidative stress. These PSMs have been shown to improve the oxidative stability of ASF (Serra, Salvatori and Pastorelli, 2021). Many PSMs also have demonstrable antimethanogenic properties.

### 3.1.6 Regulatory implications and standards

The safe use of food losses and residuals in feeds poses a significant challenge for regulatory systems. To ensure food safety, it may be necessary to establish or adapt existing standards and certification schemes for treatment methods and co-product types suitable as feed (see Section 4.2).

### 3.1.7 Mitigation measures and upcycling

Food and feed losses are critical issues with far-reaching environmental, economic and social consequences. Losses during harvest, processing and consumption must be reduced, prevented or recovered for other purposes. It was estimated that LCB for livestock could be used to produce animal protein to meet 15–45 percent of human protein requirements, thus resulting in a considerable reduction in food–feed competition (Wilkinson and Lee, 2018; Van Zanten *et al.*, 2018). It is essential to either recover and valorize the unavoidable residuals or to regenerate new materials to reduce the environmental footprint of primary products, while assessing the impact of substituting LCB for other dietary ingredients. Replacing cereals, vegetable oil and pulses, which amount to 15 percent of the total feed use, with co-product residuals and crop residues would increase the global food supply by an average of 13 percent (10–16 percent) in terms of energy and 15 percent (12–18 percent) in terms of protein content (Sandström *et al.*, 2022). There are various strategies for increasing the value of PBPs:

1. The **mechanical processing of co-products** can be impactful as the physical properties of the resulting feed ingredient can affect feed intake and digestibility. Increasing the digestion of fibre can make livestock more productive, resulting in increased profits and positive environmental impacts. Incomplete fibre digestion reduces the profitability of ruminant production by limiting feed intake and hence animal productivity, and by increasing manure production (Adesogan *et al.*, 2019). Processing methods include shredding, lacerating and macerating (Pintens *et al.*, 2023). These methods may furthermore result in improved drying, ensiling, starch utilisation and intake, as well as reduced feed sorting and improved transport and handling, due to their effect on feed ingredients' particle size.
2. Co-products of plant origin are characterized by high-fibre and low-protein content (i.e. low nutritive value). However, they may be rich in functional metabolites such as polyphenols (including flavonoids) that can support animal health (Chuang *et al.*, 2021). The **processing of poorly digestible fibrous crop residues** is one approach designed to improve their feeding value and potential use in livestock production. Exogenous enzymes may be used to complement the digestive enzymes produced by the animal or its intestinal microbial population. They increase the efficiency of digestion by liberating sugars from the lignocellulosic fraction of plant cell walls and are mainly used in monogastric animals (Sureshkumar *et al.*, 2023). Some important enzymes include non-starch polysaccharide degrading enzymes and phytases. Some commercial mixed formulations have been shown to improve nutrient digestibility, performance and/or milk characteristics (Ahmed *et al.*, 2018). Non-starch polysaccharide enzymes are produced by various microorganisms, including *Aspergillus niger*, *A. nidulans* and *A. oryzae* (Sukumaran, Singhania and Pandey, 2005) as well as *Trichoderma reesei* (Sakita *et al.*, 2022). After applying fibrolytic enzymes to lamb diets, Sakita *et al.* (2022) reported increased weight gain, improved digestibility of acid detergent fibre and a reduction of $CH_4$ yield. Phytase is generally included in monogastric diets to liberate P from phytate. In addition to capturing P, phytates may exert an antinutritional effect in monogastric animals.
3. Bacteria and yeast, the two main categories of **direct-fed microbials** used to improve co-product utilization, can be added as feed additives. Bacterial direct-fed microbials may be classified as lactic acid producing bacteria, lactic acid utilizing bacteria or bacteria of other metabolic function. Common bacterial species in direct-fed microbials include *Lactobacillus*, *Propionibacterium*, *Bifidobacterium*, *Enterococcus*, *Streptococcus*, *Bacillus*, *Megasphaera elsdenii* and *Prevotella bryantii*.
4. **Fermentation (e.g. silage)** is an energy- and cost-effective biological method commonly used to preserve and improve the nutritional value of food and feed. Most plant co-products can be ensiled, given the right anaerobic conditions. To make quality silage, care must be taken to ensure that the soluble carbohydrates are adequate to support fermentation, DM content is in a suitable range (30–40 percent) and that oxygen is excluded. Of the different microbial starter cultures used to improve ensiling, lactobacilli are the most common (Schlegel *et al.*, 2019). Lactobacilli are effective at improving nutritional properties, digestibility and rheological characteristics in food and feed, including their antioxidant properties (Yang *et al.*, 2016). They may also reduce the phytic acid content (Xing *et al.*, 2020), allergenicity, inflammation (Meinlschmidt *et al.*, 2016), off-flavours (Schindler *et al.*, 2011), and bitterness of food and feed (Schlegel *et al.*, 2019).
5. **Preservatives**, like organic acids and their salts, may also be used to improve co-product utilization, especially in the case of moist and semi-moist co-products that are sensitive to spoilage. The shelf-life of such co-products can be extended through the targeted inhibition of spoilage microorganisms like moulds and yeasts, enabling transport to and feeding on nearby farms without a loss of nutritional value.

### 3.1.8 Transport, shipping and storage

In conjunction with price, the economic viability of distributing and storing co-products plays an important role in determining how extensively they are used. Co-products have several physical characteristics that present logistical issues for their use in livestock diets. Transporting, handling, storing and feeding co-products can be challenging. The biggest obstacle to providing co-products to livestock is having to transport them from the processing plant to where livestock are fed. Depending on the co-product's final processed form, there are varying degrees of difficulty in loading, shipping and unloading. Moisture in the co-product can spoil it and lower its nutritional value, particularly when ambient temperatures are high. The shelf-life of high-moisture feed ingredients is often short, and their high-moisture content can complicate shipping by adding to the total weight of the shipment and impede product flow. Transportation technologies for co-products are constantly being introduced and improved. For example, unit trains such as 90–110 car trains are being used to ship co-products to specific locations. Some milling/processing plants have built specialized rail track loops and unloading facilities to move co-products more efficiently. Some can unload special railroad cars without decoupling them by rotating the entire car and dumping co-products into pits from which they can be distributed for mixing with other feed ingredients.

## 3.2 ANIMAL-BASED PRODUCT OPPORTUNITIES IN THE CIRCULAR BIOECONOMY

Livestock farming results in various products that leave the farm for further processing. These include live animals destined for slaughter and the production of meat, offal and their co-products, including milk, eggs and fibre (e.g. wool, mohair, camel hair). The following sections examine the range of these ABPs and a wealth of other potential co-products that can be generated during their processing, with an emphasis on opportunities for upcycling. Aligning with the principle of the value pyramid (Figure 4), here we focus on the use of co-products of livestock processing, considering regional differences (Section 3.2.1), milk processing (Section 3.2.2), wool production (Section 3.2.3), hide and skin production (Section 3.2.4), as well as co-products from egg processing (Section 3.2.5) and from aquaculture and fisheries (Section 3.2.6).

### 3.2.1 Livestock processing

#### *3.2.1.1 Products*

Livestock is processed primarily for edible products (meat and offal), but it also yields multiple other co-products, residuals and wastes with the potential to generate new alternative products of bioenergy (Figure 6). Redirecting these products towards alternative uses and away from waste streams is key to achieving circularity. Rendering is an important step in livestock processing, as it enables animals that have not been approved to be processed for human consumption (e.g. dead livestock, livestock failing inspection or carcass quality imperfection) or human-inedible products (e.g. bones, feathers) from abattoirs to be upcycled into a range of valuable co-products (Wilkinson and Meeker, 2021; Figure 6). For example, paunch (i.e. gastrointestinal content) from abattoirs is predominantly used for bioenergy, including as a source of energy in abattoirs (Karlis *et al.*, 2024), to generate compost and as a fertilizer.

An array of high-value ABPs – supporting the principle of the value pyramid (Figure 4) – are produced, with applications in the food, pharmaceutical and cosmetic industries (Table 2). New, innovative and green extractive techniques have been developed for further extraction of important molecules in co-products of the rendering industry, including pulse electric-assisted extraction, microwave-assisted extraction, ultrasound-assisted extraction, high hydrostatic pressure extraction, supercritical fluid extraction, pressurized liquid extraction, subcritical water extraction, extrusion-assisted extraction, membrane separation technologies, fermentation and enzymatic extraction (Siewe *et al.*, 2019).

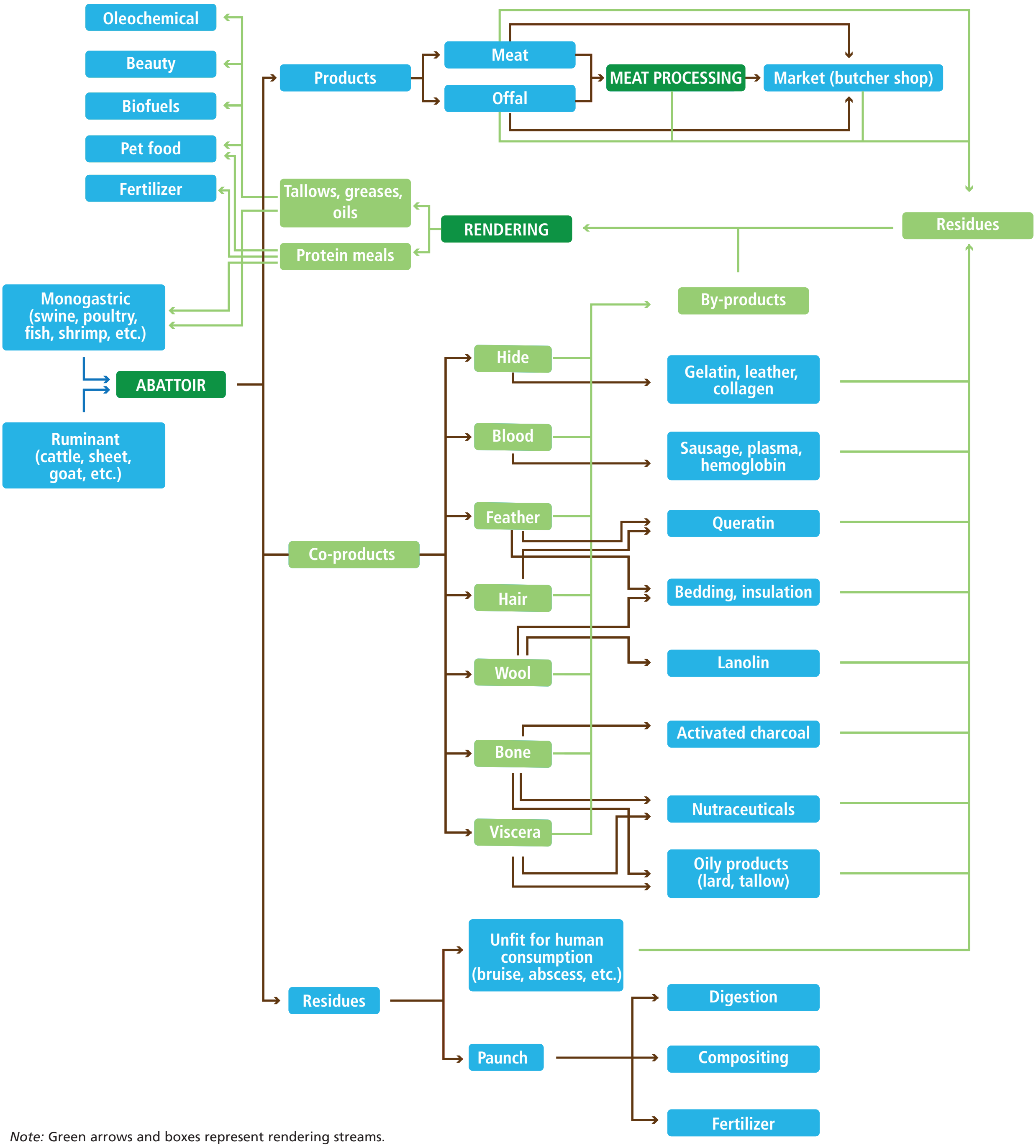
Although the general principles are valid worldwide, there are significant regional differences in livestock processing around the globe and, in many cases, this is determined by different regulatory frameworks. For animal processing in abattoirs, most developed countries have regulatory requirements relating to animal welfare, including requirements for preslaughter stunning, except when animals are slaughtered according to religious rites. In addition, there can be varying requirements relating to hygiene, food safety and meat preservation in an effort to avoid zoonotic foodborne diseases (Nastasijevic, Boskovic and Glisic, 2023). However, the greatest differences in regulations occur within the rendering sector. Table 3 gives a high-level summary of the restrictions related to animal rendering, illustrating significant regional differences. The sections related to animal processing and rendering that follow are divided up according to the regions thus defined, starting with the European Union and the United Kingdom as they have the highest requirements for ABPs (Woodgate and Wilkinson, 2021).

#### *Livestock processing in Europe*

In Europe, approximately 18.5 million tonnes of non-meat ABPs are produced by abattoirs every year. Over 13.5 million tonnes of this total come from the non-directly edible parts of the carcass declared fit for human consumption, the remaining come from the dead livestock or material not approved by official inspections at the abattoir. Some parts may be further processed to produce edible co-products, while other parts may be further processed for non-food use (EFPRA, 2022). The rendering and fat processing industries offer a vital outlet for these materials by transforming them into a wide variety of products (Figure 6). Rendering is the process of separating the fat- and protein-rich material, typically through a size-reduction mincing process followed by heating and separation (Figure 7; EFPRA, 2022). The two fractions pre-2002 in EU and UK were defined as rendered fats (RF), which is liquid at more than 50 °C or tallow, and a protein-rich solid meat and bone meal (Woodgate and Van der Veen, 2004). Following the bovine spongiform encephalopathy epidemic in 1986, the use of meat and bone meal was banned in the diet of livestock. Current EU and UK regulations apply a risk-based category approach as managed by the European Food Safety Authority, post Brexit in the UK, which is regulated by its Food Standards Agency (Table 4).

The typical composition of meat and co-products and the resulting categories from the four main terrestrial livestock species are shown in Table 5. In regards to ABP use in

FIGURE 6
**Description of multiple co-products, residues and wastes generated from abattoirs and rendering plants, illustrating various options for upcycling and increased circularity**




*Note:* Green arrows and boxes represent rendering streams.
*Source:* Scientific Advisory Panel of the World Renderers Organization (WRO), personal communication, 2023.

feed, there are key constraints in Europe. The EU regulation follows the precautionary principle, where all rendered products – rendered fat (RF), meat and bone meal – from categories 1 and 2 are prohibited as feed ingredients for livestock. Most category 1 and 2 materials are mixed and reclassified as category 1, which is then used for bioenergy production (see Section 3.2.1.9). However, protein meal from category 3, which has been redefined as processed animal protein to differentiate it from meat and bone meal, may in principle be used in feed provided that:

1. it meets strict (validated) processing conditions;
2. there is no ruminant-derived meal in any feed for livestock, i.e. ruminant protein meal is allowed in pet food only;

TABLE 2
**A summary of some high value animal-based co-products from abattoir processing**

| Product | Source | Main uses | References |
|---|---|---|---|
| Keratin | 9 to 13.2 million tonnes of global keratinous products per year, of which: • 1–2 million tonnes sheep wool • 8–10 million tonnes poultry feathers • *ca.* 1.2 million tonnes horns and hooves | Biomaterials with a wide range of uses: • pharmaceutical industry • tissue engineering • automotive industry • aerospace industry | Chukwunonso Ossai *et al.* (2022) |
| Gelatine | Pure collagenous protein. Hides from swine and cattle, fish skins and bones of swine and cattle are primary sources of gelatine. In the European Union, some sources of gelatine are prohibited for use as a feed ingredient, while in other countries, fish is a major source of gelatine. | Two types of gelatine are produced: • edible – regulated by food standards also used in feed; • pharmaceutical – regulated by the official pharmacopeia. | Gündem and Tarhan (2020) |
| Protein hydrolysates | ABP proteins hydrolysed by proteases, high hydrostatic pressure, ultrasound or other methods to obtain free amino acids and bioactive peptides. | • Functional feeds, particularly important for growing animals and those suffering from inflammation and infections; • media for cell culture; • treatment for the harmful side-effects of non-steroidal anti-inflammatory drugs in farm animals or pets; • treatment of osteoarthritis in pets. | Martínez-Alvarez, Chamorro and Brenes (2015) Fitzgerald *et al.* (2005) Marchbank *et al.* (2009) Beynen *et al.* (2010) Weide (2004) |
| Chondroitin | A complex sugar produced from processed cartilage, usually derived from cattle tracheas and pig ears but also from animal joints. | Treatment of arthritis in both humans and pets. | Singh *et al.* (2015) Bhathal *et al.* (2017) |

*Source:* See References.

TABLE 3
**Broad regional restrictions on the use of rendered products from dead animals and associated by-products**

| | Rendered products | | |
|---|---|---|---|
| | **Co-products** | **Protein meals for feeds** | **Fats for feeds** |
| European Union and the United Kingdom | Predominantly for bioenergy production (restricted use as fertilizer, if from non-ruminants). | No meals fed to species from which the meal is derived. No animal-based meals fed to ruminants. | Feeding to all livestock allowed. |
| Africa | Can be used to produce feeds (restrictions are country-specific). | Meal can be used in all livestock feeds. | Feeding to all livestock allowed. |
| Asia | Can be used to produce feeds in some countries. | Country-specific restrictions for the use of meal in feed. | Feeding to all livestock allowed. |
| North America, Australia and New Zealand | Can be used to produce feeds (with some restrictions). | No ruminant-based meals fed to ruminants. | Feeding to all livestock allowed. |
| Latin America | For soil amendment or bioenergy production only. | No animal-based meals fed to ruminants. | Feeding to ruminants not allowed. |

*Source:* Authors' own elaboration.

3. where the meal is from non-ruminant protein, there is no intra-species feeding, i.e. protein meal originating from pigs is not fed to pigs and likewise the protein meal originating from poultry is not fed to poultry.

The latter two points currently severely limit the use of protein meals in feed in Europe, given the vast quantity of protein meal produced from ruminants or mixed abattoir material. At present, ruminant or mixed protein meals containing high-value protein from numerous species are used in pet food (category 3) or as an energy source (categories 1 and 2), as discussed in Section 3.2.1.9. With Europe producing around 4 million tonnes of protein meal and 3 million tonnes of RF per year, the benefits of this resource within a circular economy are clear (Table 6).

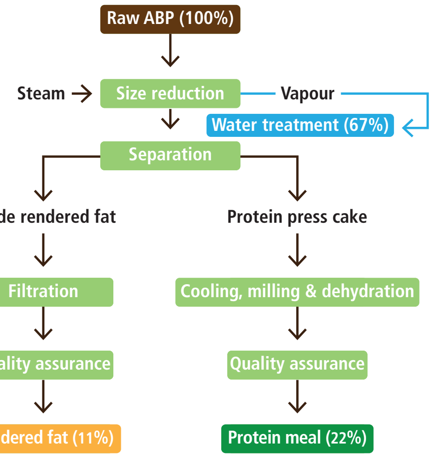
In addition to protein meal used for pigs, poultry and aquafeed, protein meal for pets can be produced from category 3 livestock species, including ruminants (Table 6). The total amount of protein meal produced by the European Fat Processors and Renderers Association (EFPRA) members is *ca*. 2 850 kilotonnes per annum (ktpa). Under the current EU legislative regime, only specific protein meals such as poultry (650 ktpa), feather (220 ktpa) or pig (420 ktpa) meal can be used as feed ingredients. As a result, approximately 1 300 ktpa of ruminant or multispecies meal can only be used as pet food. Reauthorizing the use of ruminant meal in feed would offer an alternative upcycling stream in the rendering industry. Biocircular fertilizer production is also a vital output of ABP processing (Table 6). In Europe, ABP fertilizers are split into N-rich protein meal (categories 2 and 3) producing *ca*. 200 ktpa and P-rich mineral ash following combustion (category 1 or category 2) producing *ca*. 220 ktpa. These biocircular fertilizers offset inorganic N production as well as finite fossil/mined mineral fertilizers with their high environmental cost and associated carbon footprint, which is responsible for 2 percent of global energy and 310 million tonnes of carbon dioxide emissions per annum. The use of ash from combusted category 1 is limited and is currently under assessment by the European Food Safety Authority (FEEDAP, 2024). Using a circular footprint formula, which accounts for the impact between systems, Kytta *et al.* (2021) calculated that GHG emissions were reduced by *ca*. 50 percent using a N-rich meal fertilizer as compared with inorganic mineral N fertilizer in $CO_2$eq per tonne of oat grain. Ash-based fertilizers are also high in minerals, especially phytoavailable P, making it a suitable alternative to rock phosphate (Piash *et al.*, 2023). Darch *et al.* (2019) reported on a novel fertilizer (Thallo®) produced via an elemental chemical digestion process of category 2 material at the abattoir, augmented with additional industrial co-products, resulting in the production of a bespoke mineral fertilizer that improved the nutrient profile of different soil types. This approach presents significant advantages for precision agriculture, as it not only reduces emissions at the source of production – by using recycled material with lower shipping miles – but also at the site of application.

As shown in Table 6, RF has a vast array of uses, from food ingredient (lard) to feed and pet food to biodiesel. In Europe, *ca*. 500 ktpa is also used in the oleochemical industry, which includes the manufacture of soap. However, the proportion of RF used in the manufacture of soap by saponification has declined over the last 25 years, driven by a preference for liquid soaps produced from plant-based oils such as rapeseed and palm. This shift to palm oil soaps is now being questioned in the light of a growing awareness of the environmental impact of palm oil plantations on biodiversity loss. The use of RF may be a more sustainable choice because of its biocircular credentials. Rendered-fat soap also naturally contains vitamins A, D, E, K and $B_{12}$, which reportedly contribute to skin health and appearance.

Protein meal from category 1, which can also include some category 2 products, is mainly co-incinerated in cement kilns or power stations to generate energy. Currently about 10 percent of the category 1 protein meal is used in direct-combustion (EFPRA, 2022 energy generation, where it provides energy for the rendering process), with the resulting ash used as a mineral fertilizer. In a scenario where category 1 protein meal replaced natural gas combustion in a rendering plant, Ramírez *et al.* (2012) showed that GHG emissions ranged from -1.61 to 0.40 kg $CO_2$e/kg for category 1 RF and -0.11 to 0.54 kg $CO_2$e for category 3 RF, with the lowest figures occurring when natural gas was completely replaced and the carbon emissions of the category 1 protein meal completely associated with the main product produced (i.e. carbon footprint allocated to the high-value meat and not the "zero"-value protein meal co-product). Moreover, Ramírez *et al.* (2012) postulated that, if the UK used category 3 RF and protein meals as direct replacements for palm oil and SBM, $CO_2$e emissions would be reduced annually by *ca*. 70 ktpa, a quantity that would offset emissions associated with land-use change (LUC).

FIGURE 7

**Distribution of co-products (percent) that arise from typical rendering of animal-based products (ABP)**




*Source:* Adapted from EFPRA (European Fat Renderers and Processors Association), 2022. Sustainability Charter for a circular bioeconomy, p. 11. Brussels, EFPRA. https://efpra.eu/wp-content/uploads/2022/05/EFPRA-SUSTAINABILITY-CHARTER-V1a.pdf

### *3.2.1.3 Livestock processing in Africa*

Livestock processing plays a significant role in the African continent's economy and food security. Africa has a diverse range of livestock species and the processing industry encompasses various ABPs. These include beef, sheep, goats, pigs and poultry. In Africa, countries with the highest beef production volumes are South Africa (1 038.7 tonnes), the United Republic of Tanzania (486.7 tonnes), Chad (472.9 tonnes), Ethiopia (433.1 tonnes), Sudan (389.4 tonnes) and Nigeria (326.4 tonnes). The leading exporters of beef in Africa are Botswana, Namibia and South Africa. These countries are known for producing high-quality beef for both regional and international markets. Namibia is renowned for its beef processing industry and has modern abattoirs that process cattle for export (mainly to the European Union), including premium cuts and biltong (dried cured meat). The livestock processing industry in Africa generates

TABLE 4
**Classification of the categories of animal co-products**

| Category | Definition |
|---|---|
| 1 – Highest risk | • carcasses and all body parts of animals suspected of being infected with transmissible spongiform encephalopathy<br>• carcasses of wild animals suspected of being infected with a disease that humans or animals could contract<br>• carcasses of animals used in experiments<br>• parts of animals contaminated as a result of illegal treatments<br>• international catering waste<br>• carcasses and body parts from zoo and circus animals or pets<br>• specified risk material (body parts, that pose a particular disease risk, e.g., cow's spinal cords) |
| 2 – High risk | • animals rejected from abattoirs due to having infectious diseases<br>• carcasses containing residues above the minimum limit from authorized treatments[1]<br>• unhatched poultry that has died in its shell<br>• carcasses of animals killed for disease control purposes<br>• carcasses of dead livestock<br>• manure<br>• digestive tract contents |
| 3 – Low risk | • carcasses or body parts passed fit for humans to eat at a slaughterhouse<br>• products or foods of animal origin originally meant for human consumption but withdrawn for commercial reasons and not because they are unfit to eat<br>• domestic catering waste<br>• shells from shellfish with soft tissue<br>• egg, egg by-products, hatchery by-products and eggshells<br>• aquatic animals, aquatic and terrestrial invertebrates<br>• hides and skins from slaughterhouses<br>• animal hides, skins, hooves, feathers, wool, horns and hair that had no signs of infection disease at death<br>• processed animal proteins (PAP)[2] |

[1] Clarified by the TAG members as containing residues of authorized treatment above the maximum residue limit.

[2] According to the TAG members, PAP may be fed to animals under certain conditions.

*Source:* Adapted from Guidance on animal by-product categories, site approval, hygiene and disposal. In: *GOV.UK*. London. [Cited 16 July 2025]. https://www.gov.uk/guidance/animal-by-product-categories-site-approval-hygiene-and-disposal

hides and skins, offal and high-value by-products as well as protein meal and RF, in addition to a range of more African-specific co-products (Rich *et al.*, 2022). These include:

**Bone meal** made from ground animal bones as a source of Ca and P, which are essential for bone development and overall animal health. Bone meal is often added to feeds for poultry and monogastric animals.

**Blood meal** is a protein-rich feed ingredient made from blood collected during slaughter. It is a good source of amino acids and is often used as a high-protein supplement in ruminant diets, including cattle and sheep. Blood meal is also used in aquaculture.

**Poultry/chicken meal** is a co-product of the poultry industry, derived from the rendering of offal, feathers and other parts of slaughtered poultry. It is rich in protein, essential amino acids and minerals, making it a common ingredient in livestock and aquaculture feeds.

These examples underscore the diversity of livestock processing activities across Africa, reflecting the continent's rich agricultural resources and the vital role of ABPs in local consumption and international trade alike. It is important to note that the scale and extent of livestock processing differ widely across the African continent, impacted by factors such as infrastructure, resources and market demand. The processing methods employed also vary depending on the region. Regulations and standards for using ABPs in feed are inconsistent or lacking in some African countries, making it challenging to ensure product safety and quality (Table 7). In addition to those listed in Table 7, other African countries – including Benin, the Democratic Republic of the Congo, the Central African Republic, Chad, Equatorial Guinea, Mali, the Niger, Somalia, South Sudan and Togo – may either lack comprehensive regulatory frameworks for livestock processing or have poorly defined regulatory frameworks.

In Africa, the livestock processing industry can produce processed meat products, pet food, leather, gelatin and other high-value goods by availing itself of offal and other co-products. This approach makes the livestock sector more economically viable and reduces the environmental impact by utilizing the entire animal. Feed is a significant component of the livestock industry, and a circular bioeconomy increases sustainable feed production by reducing the reliance on feed ingredients, such as SBM and fishmeal, which

TABLE 5

**Typical composition of meat and animal co-products from livestock farmed for food and their categorization in Europe**

| | Cattle | Sheep | Pigs | Poultry |
|---|---|---|---|---|
| Description | Meat and meat products intended for human consumption | | | |
| % animal liveweight | 60 | 55 | 70 | 68 |
| Description | Animal co-products NOT intended for human consumption | | | |
| % animal liveweight | 40 | 45 | 30 | 32 |
| % ABP category 1 | 3 | 5 | 0 | 0 |
| % ABP category 2 | 17 | 12 | 11 | 3 |
| % ABP category 3 | 20 | 28 | 19 | 29 |

*Note:* See Table 4 for the definition of categories 1–3.

*Source:* Adapted from Woodgate, S.L. 2023. Meat industry by-products: A bio-refinery approach to the production of safe, value added products for sustainable agriculture applications. *Frontiers in Animal Science*, 4. https://doi.org/10.3389/fanim.2023.1259200

TABLE 6

**Potential applications and amounts of derived products from the rendering animal-based products (ABPs) in Europe**

| ABP category | EU category 3 ABP | | EU category 2 ABP | EU category 1 ABP |
|---|---|---|---|---|
| ABP Input | Non-ruminant | Ruminant | Non-ruminant and calves | Specified risk material (SRM) and whole animals containing it[1] |
| Primary products | Processed animal protein and rendered fat (RF) | Processed animal protein and RF | Meat and bone meal and RF | Meat and bone meal and RF |
| **Applications** | | | | |
| Livestock feeds | ✓[2] | ✕ ✓[3] | ✕ | ✕ |
| Pet foods | ✓ | ✓ | ✕ | ✕ |
| Agronomy/fertilizer | ✓ | ✓ | ✕ ✓[4] | ✕ |
| Oleochemicals | ✓ | ✓ | ✕ ✓[5] | ✕ |
| Biofuels (transport) | ✓ | ✓ | ✓ | ✕ |

[1] Mainly ruminant but also including all livestock that died (or euthanized) through disease or accident and non-livestock animals (pets, zoological and research animals).

[2] No intra-species processes animal proteins feeding (i.e. no pigs to pigs or poultry to poultry).

[3] RF from ruminants is allowed in the European Union but processed animal protein is not.

[4] Following pressure sterilization. Biogas residue and composting can be applied to land.

[5] Restricted use to manufacture technical soaps and detergents.

*Source:* Adapted from Woodgate, S.L. 2023. Meat industry by-products: A bio-refinery approach to the production of safe, value-added products for sustainable agriculture applications. *Frontiers in Animal Science*, 4. https://doi.org/10.3389/fanim.2023.1259200

may contribute to deforestation and overfishing. Instead, alternative feed ingredients such as protein meals can be used, reducing the pressure on natural resources and promoting a more sustainable feed production system.

#### *3.2.1.4 Livestock processing in Asia*

Asia is the largest meat producing region in the world, contributing *ca*. 151.9 million tonnes, approximately 40 percent of the global production (FAO, 2021a). China makes the biggest contribution to livestock production in Asia, mainly from pork and poultry, making up 56 percent and 28 percent of its total meat production, respectively. China, the Republic of Korea and Viet Nam have the highest per capita pork consumption. In South Asia and Southeast Asia, pork production is limited and concentrated mainly in Viet Nam and Thailand (OECD and FAO, 2022). China, India, Pakistan, Türkyie and Uzbekistan are the top beef producers in the Asian region, with China and India accounting for 35.8 percent and 21.6 percent of production, respectively (FAO, 2021a). In Asia's high-income nations, cattle, pigs, camels, goats, sheep and poultry are the main sources of meat. The most common types of meat consumed in Asia are pork, chicken and beef, except for Muslim nations such as Bahrain, Kuwait, Oman, Qatar, Saudi Arabia and the United Arab Emirates, where halal beef, sheep meat, goat meat, deer, chicken and turkey are consumed, while blood, pork and carnivore meat are prohibited. The livestock processing industry in Asia generates various co-products, notably protein meals and RF. A survey found that approximately 11.4 percent and 7.5 percent of the total revenue comes

TABLE 7

**Level of regulatory requirements and standards for animal-based products (ABP) in African countries**

| Low to medium regulatory control | Medium to high regulatory control | High regulatory control |
|---|---|---|
| • Ethiopia<br>• United Republic of Tanzania<br>• Uganda<br>• Senegal<br>• Malawi<br>• Cameroon | • Ghana<br>• Côte d'Ivoire<br>• Kenya<br>• Nigeria<br>• Zimbabwe<br>• Zambia<br>• Gambia | • Egypt<br>• Morocco<br>• Rwanda<br>• South Africa<br>• Botswana |

*Source:* Authors' own elaboration.

TABLE 8

**Level of regulatory requirements and standards for animal-based products in Asian countries**

| Low to medium regulatory control | Medium regulatory control | Medium to high regulatory control | High regulatory control | No/unknown level of regulatory control |
|---|---|---|---|---|
| • Bhutan<br>• Bangladesh<br>• Cambodia<br>• Viet Nam | • India<br>• Pakistan<br>• Philippines | • Indonesia<br>• Malaysia<br>• Thailand<br>• Russian Federation<br>• Türkiye | • China<br>• Japan<br>• Republic of Korea<br>• Singapore | • Afghanistan<br>• Islamic Republic of Iran<br>• Iraq<br>• Kazakhstan<br>• Mongolia<br>• Myanmar<br>• Nepal<br>• Democratic People's Republic of Korea<br>• Qatar<br>• Sri Lanka<br>• United Arab Emirates |

*Source:* Authors' own elaboration.

TABLE 9

**Regional differences across Asia in the use of blood-based products**

| High-income countries | Middle-income countries | Low-income countries |
|---|---|---|
| • In China and the Republic of Korea, blood is consumed as blood sausage, blood tofu, blood pudding, cakes, etc.<br>• Using pig blood in feeds has been forbidden in China since the outbreak of African swine fever.<br>• In Japan, the use of blood in feed is restricted. Highly purified blood is used to produce albumin, globulin, prothrombin, fibrinogen, monoclonal antibodies, immunoglobulin (IgG, IgM and IgE) (USDA APHIS, 2023).<br>• Animal blood products are prohibited in Singapore. In Muslim countries such as Qatar, Saudi Arabia and the United Arab Emirates, the use of blood in food is restricted. | • In Bangladesh, blood is not consumed, but it is used in fish feeds and for research purposes (Abdulla *et al.*, 2020).<br>• Blood is used in foods in some regions of India, despite the ban on collecting and using the blood of slaughtered animals (Sharma *et al.*, 2021).<br>• Blood is used for the preparation of traditional dishes in Indonesia, the Philippines, Thailand and Viet Nam. | • Nepal has its own version of blood sausage, which is called *gyuma*. |

*Source:* See References.

from the non-meat co-products of beef and pork, respectively (Sharma *et al.*, 2021). There is a growing interest in harnessing these residuals and co-products, which hold significant potential for value addition. While the extent of regulation governing the processing of abattoir-derived ABPs often reflects a country's economic conditions (Table 8), the adoption of modern technologies for the efficient management of ABPs is strongly encouraged. The feed industry in Asian countries use animal blood (Table 9) and bones, which are also consumed as food in certain regions.

In Asia, bones, horns and hooves make up 11 percent of pork carcasses, 15 percent of beef carcasses and 16 percent of lamb carcasses. Bones and horns are used to produce buttons, combs, melamine utensils and other products. Cattle hooves are used for making gelatin and musical instruments (guitar nails). Bones and horns of domestic livestock are also used in crafts and for artistic purposes in China, India and Mongolia. In Bangladesh, animal bones are primarily used to produce melamine, pharmaceuticals and industrial cleaners (Abdulla *et al.*, 2020). Feathers from the poultry sector are used in feed and fertilizers, for decorative purposes and as bedding. Chicken feathers also used in pharmaceuticals, biofuel, cosmetics, bioplastic, keratin and biofibre production (Tesfaye *et al.*, 2017). In countries that lack processing facilities, feathers are landfilled.

#### *3.2.1.5 Livestock processing in Latin America*

South American countries have many large abattoirs that follow stringent processing standards to meet the varying quality and hygiene requirements of importing countries. Government regulations in Argentina, Brazil, Mexico, Uruguay and other Latin American countries ban the feeding of ruminant proteins to ruminants because of the risk of bovine spongiform encephalopathy and limit the use of dead livestock for fertilizer or energy production. These countries allow the use of all ruminant protein meals and RF for non-ruminant and pet food (Table 3).

Cultural differences can bear on the extent to which a range of edible cuts for livestock are consumed (Toldra *et al.*, 2012) and, thus, on the relative amount of animal parts available as co-products for use as feed, a source of biofuel and fertilizer. In Latin America – as in Asia and Africa – a wide range of offal is typically consumed by humans, whereas in northern Europe, North America, Australia and New Zealand most offal is not consumed but rendered. In some region of Latin America, less than 40 percent of slaughtered livestock carcasses are rendered: in Costa Rica, for example, the rendering rates for bovine, pig and chicken carcasses are 49 percent, 44 percent and 37 percent, respectively (Leiva *et al.*, 2018), while in Brazil they are 38 percent, 20 percent and 28 percent, respectively (ABRA, 2022). In contrast, the rendering percentages may be nearer to 50 percent in Europe, North America, Australia and New Zealand. In Argentina, Brazil and Mexico, RF is widely used in the oleochemical, hygiene and cleaning sectors, as well as in the production of certain food ingredients. In Latin America, most RF is consumed domestically, although since 2022 there has been an increase in RF exports. Poultry oil is mainly used in livestock feeding, aquaculture feeding and pet food in all countries. In Brazil, paunch is pressed and used as an energy source in boilers.

#### *3.2.1.6 Livestock processing in North America*

In the United States of America and Canada, approximately 31 million tonnes of ABP are available annually (NARA, 2020) for further processing through rendering. Excluding products that move directly to pet food processors (organs and poultry co-products), non-meat ABP (15.7 million tonnes) comprise 57 percent protein meals, 40 percent RF and 3 percent plasma meal. The three largest co-products by weight are RF (24 percent), hides (22 percent) and protein meals (21 percent) for beef; blood (24 percent), protein meal (13 percent) and plasma (13 percent) for pork; bones/frames (34–51 percent), feathers (21 percent, chickens), blood (14 percent) or viscera (8–14 percent) for poultry. In 2023, about 67 percent of beef RF was used for biofuel production, whereas only 7 percent of poultry RF was used for biofuels (USDA National Agricultural Statistics Service, 2024; US Energy Information Administration, 2024). The production of protein meal increased by 3.9 percent compared to that of 2022, driven by the growth of global export markets.

Rendered ruminant protein meal cannot be fed to ruminants and there is no limitation of intra-species use. However, bovine plasma may be used as cattle feed and hydrolysed feather meal as poultry feed. Apart from protein co-products and fats, the pet food industry also uses dehydrated meat "broth" in most dry dog and cat foods, and wet in wet pet foods (NARA, 2020).

#### *3.2.1.7 Livestock processing in Australia and New Zealand*

Australia and New Zealand are the largest exporters of sheep meat and major exporters of beef. In New Zealand, more than 90 percent of ABPs are exported, representing 19 percent of total revenue (81 percent from meat products) from livestock, 4 percent of it from rendered protein meal (i.e. mainly for fish feed) and RF (i.e. mainly for biofuel) (MIA, 2022). This includes rendering of dead livestock under strict rules.

Some rendering operations in Australia and New Zealand use low-temperature energy systems for rendering (Rendertech, 2019). This process removes water by physical compression through a screw press, which offsets the initial heating and lowers the overall energy needed to dehydrate protein meal and RF. By requiring less energy than high-temperature rendering, this process results in reduced GHG emissions. This helps ensure that the upcycled products have a significant net benefit as a result of reduced energy use and emissions during production.

The choice between low- and high-temperature processing is often driven by the relative costs of capital, electricity, gas, fuel and biomass. Exceptions arise when dealing with thermo-sensitive raw materials. For instance, low-temperature rendering of fish co-products has been shown to yield higher-quality fish oil and meal compared to high-temperature methods (see Section 3.2.6).

In Australasia, many livestock processing plants use slaughtering methods that meet Halal requirements. This practice complicates blood collection from slaughtered livestock for food or pharmaceutical purposes, since it carries an increased risk of hair and ingesta contamination. Pharmaceutical-grade blood collection is common in New Zealand abattoirs for plasma or serum, despite the lower yield from Halal-slaughtered animals. One company processes over 2 million litres of blood from New Zealand abattoirs to produce a range of blood-derived products, including serum for cell culture and biomedical purposes, bovine serum albumin used as a carrier for various drugs and pro-thrombin used in blood-coagulation control. In 2022, exports of blood products and glands from processed cattle and sheep generated over USD 130 million, accounting for more than 2 percent of the total revenue from New Zealand beef and sheep meat (MIA, 2022). This collection and processing of blood into high-value pharmaceutical products is an example of upcycling along the value pyramid (Figure 4).

In Australia and New Zealand, most RF is exported to Southeast Asia and the United States of America for biofuel production. Paunch collected from abattoirs in New Zealand is mostly used for specialist compost production, as a valuable source of organic matter and nutrients for horticultural crops.

#### *3.2.1.8 Nutritional value of animal-based products as feed ingredients*

Dietary protein is a vital component of any animal feed as it supports body functions, growth, muscle development and other production processes (i.e. eggs and milk). It is also the costliest component of the ration, financially and often environmentally. Currently, SBM is the most common protein source fed to confined livestock. More sustainable, circular protein sources are critically needed. Protein meals from rendered ABPs represent a potentially valuable source of protein, with a digestibility between 75 percent and 94 percent and a high biological value (up to 8.70 percent lysine and 1.40 percent methionine), depending on the sourced meal (Heuzé *et al*., 2015f, 2016a).

Research indicates that many of these sources could substitute SBM in the diets of pigs and poultry, and in aquaculture. Protein meal can account for 5 percent to 25 percent of the diets of poultry and pigs, supplying one third of the dietary protein (Leiva *et al.*, 2018). Studies involving pigs, in which SBM was replaced by protein meal, have yielded mixed results. Shelton *et al.* (2001) reported lower performance of growing-finishing pigs offered protein meal compared to SBM. In contrast, Gottlob *et al.* (2004) reported improved average daily gain when protein meal constituted up to 5 percent of the diet, and that it still performed as well as SBM at higher incorporation rates. In poultry, replacing SBM and dicalcium phosphate with protein meal at 2 percent, 4 percent or 6 percent had no impact on egg mass (i.e. more eggs with lower weight), the feed-conversion ratio, body weight or mortality (Bozkurt, Alçiçek and Cabuk, 2004). In aquaculture, the suitability of protein meal as a substitute for SBM has also been demonstrated in a range of fish species (Rossi and Davis, 2014 in the case of *Trachinotus carolinus L.*; Moutinho *et al.*, 2017 for *Spraus aurata;* and Mohsen and Lovell, 1990 for *Ictalurus punctatu*).

That said, because of the nature of protein meal production, its composition, quality and nutritional value as a sustainable protein feed ingredient depend on the nature of the material from which it is derived (Hendriks *et al.*, 2002). In addition, the level of protein meal incorporated into livestock diets may also be limited by its mineral content. Solá-Oriol, Roura and Torrallardona (2011) reported that pigs preferred feeds with 5 percent protein meal to SBM. However, values greater than 5 percent reduced feed intake, probably because of the high mineral content in some protein meals.

As a source of high-quality protein, vitamins and minerals, protein meal is an essential ingredient in pet foods and cannot be easily replaced by PBPs. This is especially true of cats which, as carnivores, specifically require taurine, a nutrient lacking in all PBPs. In addition to their nutritional value, protein meals have been shown to make pet foods more palatable (Boskot, 2009). However, the use of such ABP protein meals requires careful processing to ensure safety and compliance with national regulations (Section 3.2.1).

Rendered fats are also a key ingredient in feed, as well as being essential for the food sector, since – depending on the production system – they can offset environmental impacts associated with palm and soybean oil production. Palm oil replaced RF in many food products because of specific health concerns (palmitic acids [C16:0] and stearic acids [C18:0]). However, it has since been shown that C16:0, which is present in higher concentration in palm oil than RF, raises low-density lipoprotein (LDL) cholesterol, whereas C18:0 (i.e. predominantly saturated fatty acids in RF) does not raise LDL cholesterol, possibly because of its rapid conversion to oleic acid in the body (Grundy, 2013).

With rising interest and financial returns in the pet market, ABPs are increasingly being included as functional ingredients in pet foods, either as nutraceuticals (Table 2) or to improve protein digestibility in the case of pancreatin, a digestive enzyme extracted from pigs' pancreases that helps to break down and digest food (EFSA, 2023). In addition, other ABPs are used as pet treats, including pigs' ears, rawhide and bones (Martínez-Alvarez, Chamorro and Brenes, 2015).

Dietary minerals (especially Ca and P) are important for skeletal development, milk composition and eggshell production. Mined phosphate rock and limestone are currently used as sources of P and Ca, but protein meals and bone meals are also a source of highly digestible Ca and P. Bozkurt, Alçiçek and Cabuk (2004) showed that replacing dicalcium phosphate with protein meal in the diet of layers improved egg quality (specific gravity and Haugh unit) and eggshell integrity (fewer cracked/broken eggs).

#### *3.2.1.9 Environmental risks, benefits and assessments*

Rendering plays a critical role in turning animals or ABPs unsuitable or unwanted for human consumption into valuable products, thus supporting a greater circularity through upcycling (Table 6). This also helps to avoid problems associated with sending unwanted materials to landfill, resulting in increased $CH_4$ emissions and the risk of groundwater contamination. Using RF and protein meal as feed ingredients can replace PBPs, reducing pressure on agricultural land and the overall carbon footprint of the product (Box 7). Abattoirs produce wastewater during plant cleaning, animal excreta in yards prior to slaughter and liquids (e.g. blood, paunch). If these are voided into waterways, they can contribute to eutrophication. In many parts of the world – Europe, Australia, New Zealand, Latin America and North America – strict regulations limit the discharge of wastewater into waterways to reduce the risk of eutrophication. Wastewater from processing plants, such as that generated during the cleaning and washing down of yards used to hold animals before slaughter, is commonly applied to agricultural land as a substitute for chemical fertilizers. Even greater benefits could be derived from wastewater, if it were stored in ponds prior to land application and if the $CH_4$ emitted were captured for bioenergy use. Other nutrient recovery and recycling options could be employed to recover valuable elements such as N and P. Once captured, these nutrients could be used as fertilizers in agricultural systems as described in Section 3.3. This approach would lessen the reliance on synthetic fertilizers, conserve natural resources and prevent nutrient pollution of water bodies.

#### *3.2.1.10 Energy (biofuels, electricity)*

Rendered ABPs can also serve as a sustainable energy source (Table 6). Rendered fats converted to biodiesel via transesterification (Bhatti *et al.*, 2008) resulted in biodiesel with cetane values (in a quality assessment based on fuel ignition) that often exceeded 60, owing to its high saturated fatty acid content. In contrast, PBP biodiesels usually have a cetane of between 48 and 52. The higher cetane numbers result in higher engine performance and reduced carbon emissions. Although biodiesels are associated with lower carbon emissions than petrodiesels, they often have marginally higher emissions of nitrous oxides (McCormick *et al*., 2001). Rendered-fat biodiesels present other challenges, such as high viscosity, potential polyethylene contamination (e.g. plastic ear tags) and high sulphur levels, which limit their effectiveness as a substitute for petrodiesel. Of the 6.3 million tonnes of RF produced from ABPs in the United States of America, approximately 10.30 percent (644 kilotonnes) are classified as animal fats and utilized to produce biofuels (i.e. biodiesel and sustainable aviation fuel; EIA, 2018), in addition to 918 kilotonnes (14.60 percent of total RFs) classified as recycled yellow grease or other. This represents an important biocircular energy source (*ca.* 52 trillion kilocalories) recovered by ABP rendering plants. In Asia, ABPs unsuitable for other purposes are mainly used to produce biogas. In China, biogas facilities produce 150 $m^3$ to 500 $m^3$ of biogas daily. According to the Chinese biogas sector, 41.9 million biogas digesters have been erected, producing 14.5 billion $m^3$ of biogas annually (Abanades *et al.*, 2021). In 2021, China generated 5597 gigawatt-hours of energy from biogas (STATISTA, 2023). In 2019, 221 biogas plants with a total capacity of approximately 85 megawatts were operating in Japan. The main substrates for use in biogas plants in Japan are food waste, livestock manure and sewage sludge (European Union–Japan CIC, 2021). In the past ten years, AD has been increasingly used to produce biogas and manage municipal waste in Japan (Abanades *et al.*, 2021). Small-scale and household biogas systems have also been widely adopted by countries like India and Bangladesh (Abanades *et al.*, 2021).

Livestock processing facilities in Africa hold great potential for integrating renewable energy systems in a bid to reduce reliance on fossil fuels and decrease GHG emissions. These renewable energy solutions not only reduce the industry's carbon footprint but also provide opportunities for decentralized energy production that would benefit rural communities.

#### *3.2.1.11 Constraining factors for greater adoption*

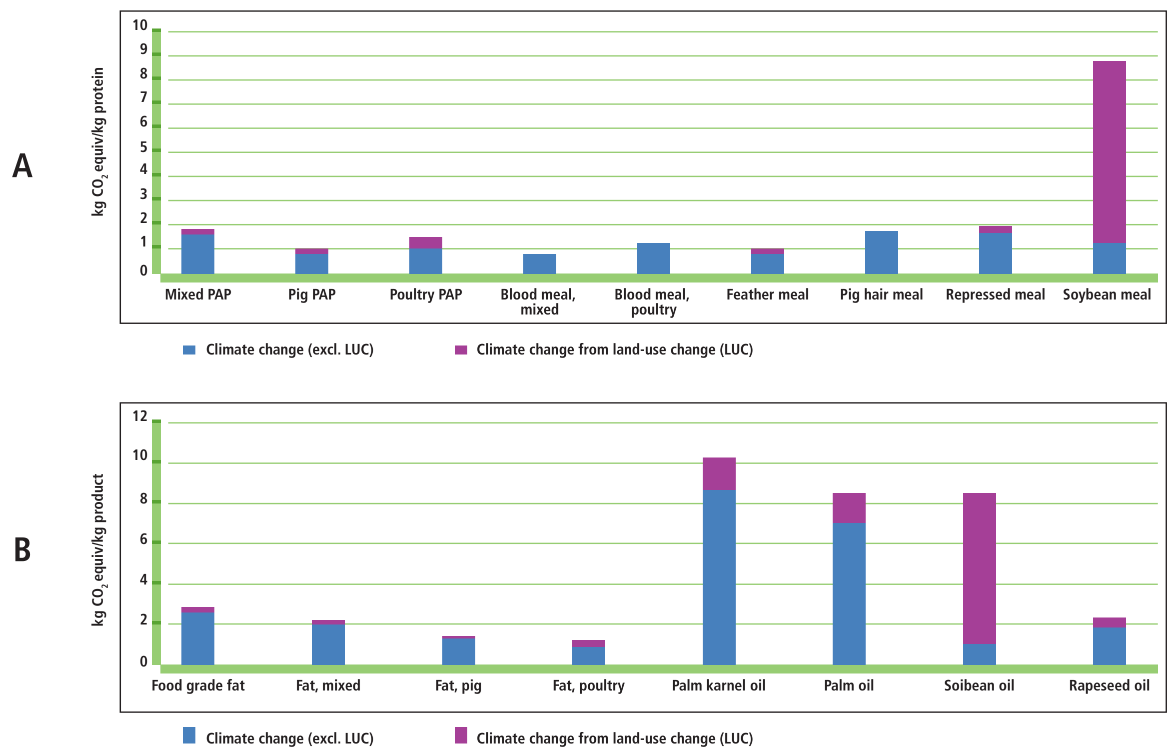
In Europe, the vast untapped potential of ABPs to contribute to the circular bioeconomy and reduce the environmental footprint of livestock – for example, by choosing RF over palm oil, protein meal instead of SBM, and RF biodiesel rather than petrodiesel – is restricted by significant regulatory challenges. The bovine spongiform encephalopathy epidemic in 1986 highlighted the importance of the rendering industry as a crucial component in the food supply chain. Woodgate and Wilkinson (2021) described how economically driven changes in the rendering sector during the 1980s led to a failure to deactivate the prion proteins responsible for transmissible spongiform encephalopathies such as bovine spongiform encephalopathy and scrapie. Subsequent transmissible spongiform encephalopathy deactivation trials showed that a traditional ren-

BOX 7

**Summary of carbon footprint assessment of co-products from rendered livestock in Europe relative to common alternative crop-based products**

Rendering of animal-based products (ABPs) in Europe is essential for upcycling materials that might otherwise go to waste or be limited to lower-value uses such as bioenergy, fertilizer or compost. Koukouna and Blonk (2020) drew on the joint Global Feed LCA Institute and LEAP attributional life cycle assessment methodologies to compare the greenhouse gas emissions of rendered co-products to those of commonly used crop-based products. The economic allocation of category 3 products with no post-abattoir value – including pig hair, poultry bones and fat, head, blood and processed animal proteins – also lacked prerendered emission estimates. Emissions from the rendering process were included, along with all farm and abattoir emissions associated with products of economic value. Land-use change (LUC) emissions related to on-farm feeds were also accounted for. The average carbon footprint of alternative crop-based products, such as rapeseed meal, soybean meal (SBM) and oils from various crops, were obtained using the methodology developed by the Global Feed LCA Institute.

The results (Figure A and Figure B) for meals (on a protein basis) show a variation between ABPs related in part to their abattoir prices. The emissions from ABPs were lower than those from crop-based meals, notably for SBM because of its contribution to LUC. This also applied to the fats vs oils comparison (Figure B), where the ABPs had a lower carbon footprint than crop-based oils.




*Note:* A = animal protein meals (expressed in kg protein) and B = fats and oils.

*Sources*: Koukouna, K. & Blonk, H. 2020. Carbon footprint assessment of co-products from rendered livestock in Europe. Gouda, Kingdom of the Netherlands and Arlington, USA, Blonk Consultants/Global Feed LCA Institute; EFPRA (European Fat Processors and Renderers Association). 2024. Life Cycle Assessment of rendered products: Carbon and water footprints. White paper. Brussels, EFPRA. https://efpra.eu/wp-content/uploads/2024/12/White-Paper-GFLI-Feed-Ingredients-Final.pdf

dering system with a hyperbaric pressure stage of 3 bars for 20 minutes resulted in transmissible spongiform encephalopathy being brought down to below detectable levels (Woodgate and Wilkinson, 2021). This created the potential for the reintroduction into the feed industry of valuable ruminant protein meal as a source of sustainable high-quality nutrition. The European Union has adopted a more cautious risk-based approach (see Section 3.2.1.2) than the rest of the world regarding the utilization of animal protein meals in feeds, limiting the market and economic value of rendered products. At present, in Europe, protein meal from ruminants can only be used in pet food. However, protein meal from ruminants can be used safely in omnivorous (aquaculture, pigs and poultry) livestock diets.

Bozkurt, Alçiçek and Cabuk (2004) demonstrated the potential of beef protein meal to improve the performance of laying hens. Moreover, category 1 and 2 materials can be used to extract high value by-products, as noted by Pérez-Aguilar, Lacruz-Asaro and Arán-Ais (2022). These findings highlight the need for further research and a wider commercial acceptance of proven, safe biocircular resources with higher-value applications (Figure 4).

Safety measures rely on thermal processes, especially to reduce the risks associated with microorganisms or pathogenic organisms. However, these processes must be carefully controlled, as overcooking can damage protein quality. Furthermore, the moisture content of ABPs should be kept low (≤10 percent) to avoid microbial growth and contamination (Leiva *et al.*, 2018).

Other constraints to consider include water pollution and odours. The combination of microbiological load, heat, moisture and time are ideal conditions for the formation of odours and soluble pollutants. Most problems can be resolved through prompt processing and/or chilling; however, this is not always possible with ABPs destined for rendering. To effectively implement a livestock circular bioeconomy in Africa, it is crucial to foster technological innovation, partnerships among stakeholders and supportive policy frameworks. The adoption of circular bioeconomy practices in livestock processing can create employment opportunities as the use of co-products gives rise to new value chains and industries. African governments should establish clear guidelines, standards and incentives to promote the use of residues, resource-use efficiency and the development of value-added products. Moreover, capacity-building programmes and training initiatives are needed to improve the knowledge and skills of stakeholders in the livestock processing sector.

Water scarcity is a significant challenge in many parts of Africa and around the world. In a circular bioeconomy, livestock processing facilities can adopt water-efficient practices such as recycling and reusing water for cleaning and irrigation. Rendering can lead to the net capture of water during processing as in the case of North America, where approximately 15 billion litres of water are reclaimed during the rendering process. Technologies like AD can be used to treat wastewater and at the same time recover biogas. Efficient water management conserves water resources and supports the sustainability of the livestock sector.

Finally, religious practices affecting the intake of different types of meat (e.g. pork in the case of Islam and Judaism; beef in that of Hinduism; all meat in Buddhism and all animal-sourced food in Jainism), dietary preferences (e.g. pescetarianism, vegetarianism and veganism) and constraints (e.g. lactose-intolerance) may limit the full potential of ABPs to be utilized in the previously discussed circular bioeconomy scenarios.

### 3.2.2 Milk processing

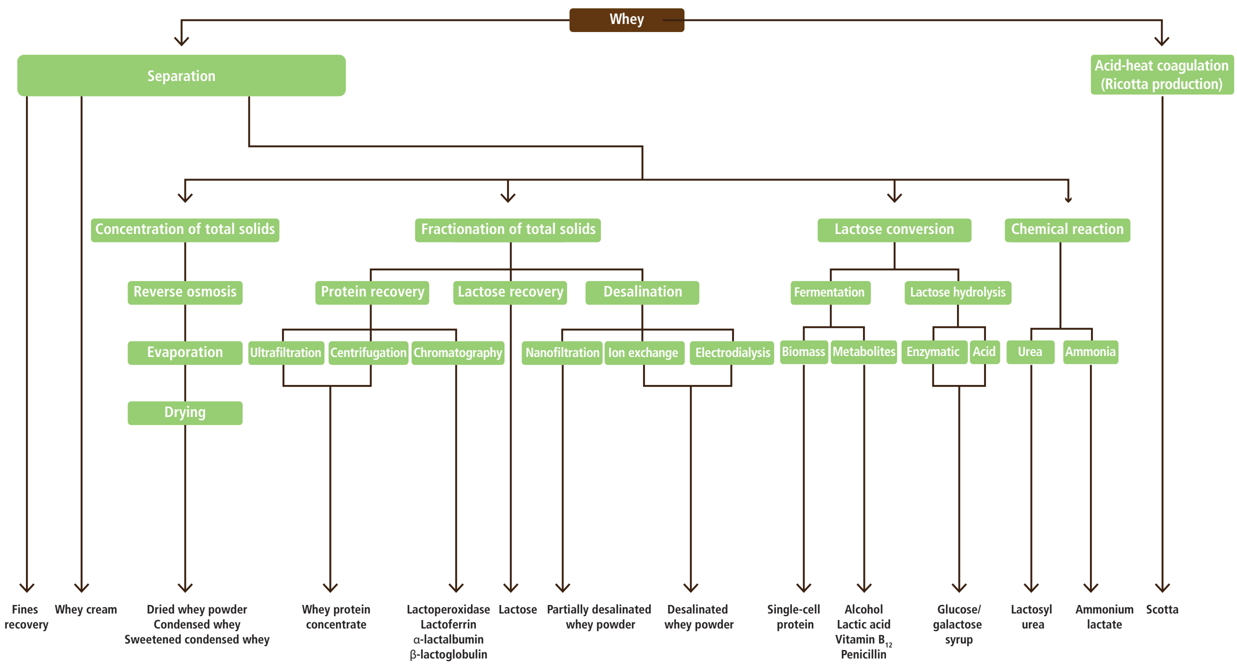
#### *3.2.2.1 Products*

In 2022, the global dairy sector produced 930 million tonnes of milk, which was processed into a wide range of dairy products for human consumption. Several co-products are generated during the processing of the major dairy products. The main one is whey, primarily from cheese and Greek yogurt production (Pires *et al.*, 2021), while others include skimmed milk, buttermilk and ghee residue. These co-products are now extensively processed into valuable by-products. Residuals and waste can include products that have been downgraded (e.g. because of damaged packaging, contamination, being out-of-date or not meeting specifications) or wastewater (mainly from cleaning production plants).

Whey is a dilute liquid that contains lactose, soluble proteins, lipids and minerals (Appendix 5). While in the past whey was often discharged into waterways, many dairy processors now apply technologies to concentrate proteins, which yields co-products such as whey protein concentrate, whey protein isolate and lactalbumin (Figure 8; Buchanan *et al.*, 2023). These whey-based products are used in various foods, infant formulas among them. Lactose is currently one of the major co-products produced from whey, with use in pharmaceuticals and as a protein-mineral precipitate for feed (Rafiq and Rafiq, 2019). Whey can be used as such to produce cheeses like ricotta (about 850 kilotonnes of whey are used in Italy, a major ricotta producer). Another liquid co-product of the ricotta production is scotta, with more than 800 kilotonnes produced in Italy in 2021. Both whey and scotta are used as feed ingredients in many countries. However, roughly 40 percent of whey remains unprocessed and recent work has shown that it can be useful in producing packaging and edible coatings (Rafiq and Rafiq, 2019). In the United States of America, near-dated milk is reprocessed to generate proteins, fats and lactose for use in feeds; specialized facilities dry the milk to maintain nutrient quality and stability and to avoid spoilage. Whey that has not been processed because of technology or cost limitations can be used as a fertilizer (Akay and Sert, 2020), but many countries have strict regulations regarding it being used in this manner. Whey has alternatively been used directly or after protein extraction for AD (Casallas-Ojeda *et al.*, 2021).

The two other main potential co-products of the dairy industry are buttermilk and ghee residue, with buttermilk often being employed in a similar manner to skimmed milk.

FIGURE 8
**Flow diagram of potential co-products generated from processing whey**




*Source:* Van Dijk, N. 2025. Whey and milk fractionation. In: *Dairy processing handbook*, chap. 16. Lund, Sweden, Tetra Pak. [Cited 19 July 2025]. https://dairyprocessinghandbook.tetrapak.com/chapter/whey-and-milk-fractionation

Skimmed milk powder is obtained by skimming the fat from milk and passing the skimmed milk through a spray-drying process. It has an extended shelf-life and is used as an ingredient in various food products and beverages, particularly in Africa and Asia. Skimmed milk is also a source of casein and caseinates, which are primarily used in edible products, with minor applications in nutraceuticals and industrial products such as textiles, adhesives and paints. In India, buttermilk co-products such as *kadhi* and *dhokla* are made with skimmed milk or buttermilk that has been spiced or salted, and sold directly for human consumption. India also produces ghee residue, some of which is used in food items such as *burfi* sweets, bakery product and chocolates, but a significant portion still goes to waste. The use of these co-products is essential for the sustainability and economic viability of dairy industries globally. Their appropriate processing and marketing can make the dairy industry more profitable, minimize waste and increase the food supply. Downgraded milk products have also been directly fed to livestock.

Wastewater (including from plant cleaning and spillage), down-graded products and whey or whey extracts have also been used as substrates for microbial fermentation, biogas production or generating ethanol, lactic acid, solvents, surfactants, enzymes, biopolymers, bioplastics, hormones, vitamins and bioactive compounds (Sar *et al.*, 2022). Wastewater has also been subject to nanofiltration and reverse osmosis to recover water for on-site use, while the retentate has been added to fermented milk beverages and *dulce de leche* which is formed from the heating of whole milk (Barbosa Brião *et al.*, 2019).

### *3.2.2.2 Nutritional value of dairy co-products*

Nutritional composition can vary widely across dairy co-products. Whey is composed of approximately 93 percent water, the remaining solids consisting of 70–72 percent lactose, 8–10 percent proteins and 12–15 percent minerals (Rafiq and Rafiq, 2019). While adding whey protein to a sports drink does not appear to affect post-exercise rehydration, its consumption following exercise may support recovery mechanisms (Hobson and James, 2015). In addition, whey protein has high bioavailability, with an estimated digestible indispensable amino acid score – used to indicate protein quality – typically ranging from 1.1 to 1.3, while that of PBP protein sources has a lower value, between 0.4 and 0.9 (Rutherfurd and Moughan, 2012). Moreover, the digestibility of whey DM in ruminants is high, reaching up to 87 percent in diets that contain 30 percent whey.

Scotta is lower in fat and protein content than whey (Appendix 5). Similar to whey, scotta protein is highly digestible and contains a large amount of branched-chain essential amino acids (isoleucine, leucine and valine), in addition to bioactive peptides (Chianese *et al.*, 1997; Caroli *et al.*, 2011).

Buttermilk's composition is generally similar to that of skimmed milk, containing 31.5–33.1 percent protein, 48.7–53.8 percent lactose, and approximately 5.7–13.1 percent fat on a DM basis (O'Callaghan, 2022).

A review of ghee residues indicated that it contains 12–27 percent moisture, 33–59 percent fat, 19–33 percent protein, 5–18 percent lactose and 1–5 percent ash, with some variation depending on the source of ghee residue (Wani *et al.*, 2022).

#### *3.2.2.3 Environmental risks, benefits and assessment*

Whey has a high biological oxygen demand (*ca*. 40–60 g/L) and chemical oxygen demand (COD) (*ca*. 50–80 g/L), which makes it a strong pollutant if released into waterways (Chatzipaschali and Stamatis, 2012). In 2016, it was estimated that less than 50 percent of the world's whey production was recycled, with most of it disposed of in drains (Macwan *et al.*, 2016). Subsequently, many countries and regions (North America, Australia, New Zealand and the European Union) adopted legislations limiting whey disposal into waterways (Zandona, Blažić and Režek Jambrak, 2021). Life cycle assessment studies on the processing of whey into co-products has yielded mixed results when compared with plant- or fossil-based alternatives, reflecting different methodological assumptions. A recent study found that whey-based bioplastics can have a lower environmental impact than plastics derived from fossil fuels. Bioplastics produced from whey using a copolymerization technique had lower GHG emissions/kg than polylactic, polypropylene, low-density polyethylene and high-density polypropylene plastics (Chalermthai *et al.*, 2021; Box 8).

### 3.2.3 Wool processing

#### *3.2.3.1 Products and potential for upcycling*

With about 1 034 million tonnes of clean wool produced annually (International Wool Textile Organisation [IWTO], 2021), wool is a major co-product of sheep production. However, the returns on coarse wool have declined in recent decades as a result of the increasing presence of synthetic products (e.g. carpets, textiles, upholstery and bedding) dominating the market. In the United Kingdom, after carpets and textiles, an important use of coarse wool is in building insulation, thanks to its insulating ability, breathability and fire-retardant properties. Coarse wool may be combined with bioresin to create a durable composite used for manufacturing a range of products, including furniture, laminates and floor tiles (Allafi *et al.*, 2022). This composite is used for a growing number of innovative, higher-value applications of this material. In the UK wine industry, additional uses of wool are being explored, such as placing fleeces around vines to retain soil moisture, deter pests such as slugs, and reflect sunlight back onto the vines to increase yield and grape quality. When coarse wool is unsuitable for more upcycled products, it can be repurposed as a fertilizer (Dal Prà *et al.*, 2024). In contrast to coarse wool, fine wool from Merino sheep as well as cashmere and mohair from goats, command a significantly higher price per kilogram because of their use in the lucrative sportswear, mountaineering apparel and suit industries. Other new uses include machine-washable shoe uppers and hygienic face-mask liners.

While wool has traditionally been used for clothing, rugs and carpets, new research has shown that it can potentially be upcycled for use as a source of human-edible protein (Giteru *et al.*, 2022). Scoured wool is 95–98 percent protein and can be hydrolysed to edible keratin (Table 2), whose high cysteine content (*ca*. 10 percent of total protein) has associated health benefits such as muscle protein development.

During the initial scouring of shorn wool to produce clean wool, wool grease is produced, from which lanolin – the main co-product – is extracted. Wool grease, which is higher in fine wool, constitutes about 5–25 percent of shorn wool (Sengupta and Behra, 2014). Lanolin has a range of uses, including in cosmetics and lubricants. Cholecalciferol (vitamin $D_3$) may be produced from the conversion of seven dehydrocholesterol present in lanolin, using ultra violet radiation. Other co-products from scouring include cholesterol and isopropyl lanolate. Conventional scouring also results in wastewater, which can be treated to generate $CH_4$ and extract nutrients for use as fertilizer.

#### *Environmental risks, benefits and assessment*

Wool scouring uses water and chemicals, and if effluent is released directly into waterways, it can negatively impact water quality. As a result, many countries have regulations on treating wastewater in place to minimize impacts. However, Kherdekar and Adivarekar (2016) showed that it is possible to dry scour wool using grease-absorbing nano-clays.

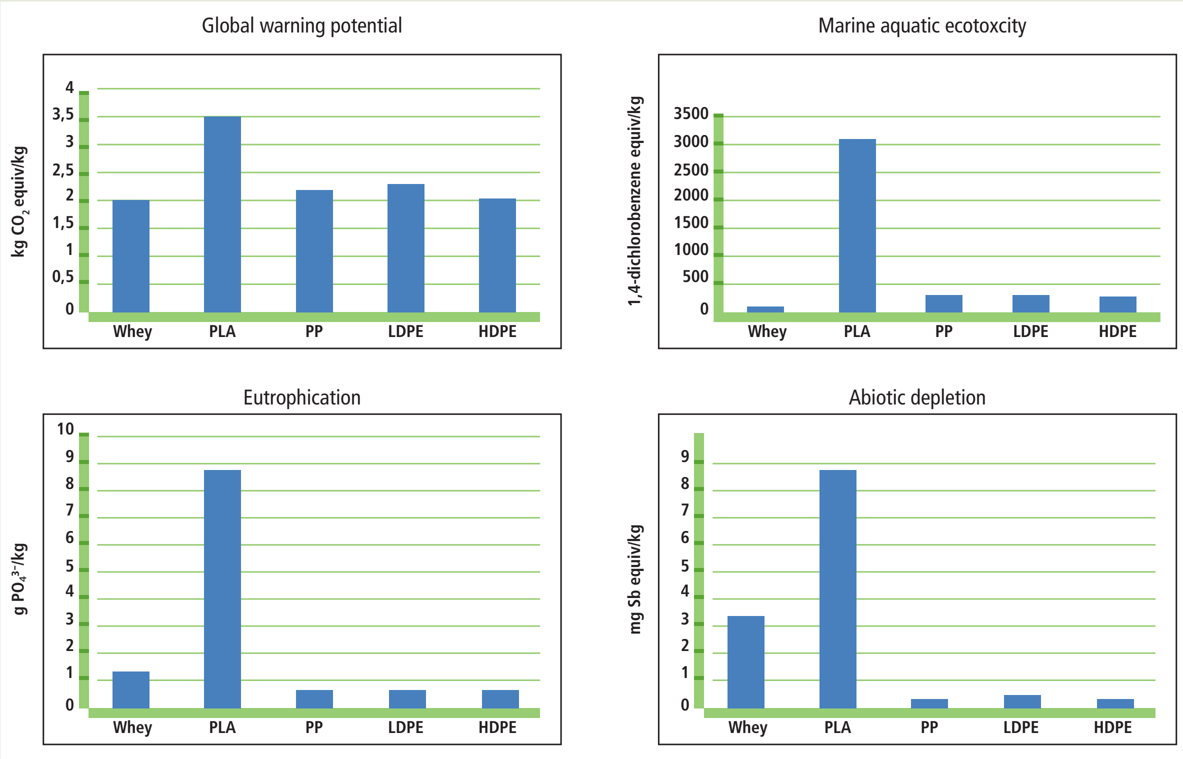
Interestingly, wool's oleophilic properties make it well-suited to absorb oil slicks at sea. The oil absorbed by the wool can be extracted by squeezing, allowing the wool to be reused multiple times (Periolatto and Gozzelino, 2015).

Environmental LCAs of wool products have revealed that most environmental impacts generally occur at the cradle-to-farm-gate stage. However, recent full life cycle studies show that wool's durability means that it often outlasts petroleum-based garments (Wiedemann *et al.*, 2020). Consumer surveys also indicate that woolen garments are worn more often and washed less, reducing use-phase emissions (Nautiyal *et al.*, 2023). In addition, wool fibres can be readily recovered and recycled into other products. When disposed of, wool biodegrades naturally and can even serve as a source of nutrients. Unlike petroleum-based

BOX 8

**Environmental impact assessment of bioplastics produced from whey in the United Arab Emirates compared to various fossil fuel-based plastics**

Bioplastics derived from proteins are an alternative to fossil fuel-based plastics. Chalermthai *et al.* (2021) used attributional life cycle assessment (ALCA) to evaluate the environmental impact of bioplastic produced from whey protein. Whey was processed using a free-radical copolymerization method to produce the bioplastic with poly(ethylene glycol) methyl ether methacrylate. The study applied ALCA (a baseline method developed by the University of Leiden's Centrum voor Milieuwetenschappen [CMCL; Institute of Environmental Science]) from the cradle to the processing gate with a functional unit of 1 kg plastic. Whey bioplastic was compared to plastics of polylactic (PLA) and fossil-based polypropylene (PP), low-density polyethylene (LDPE) and high-density polyethylene (HDPE). Whey bioplastics have the lowest greenhouse gas emissions and marine ecotoxicity impacts. They have a moderate impact on eutrophication and among the highest levels of abiotic depletion, linked to the energy needed for copolymer production. These energy-related impacts would be significantly reduced if renewable energy sources – instead of natural gas – had been relied on to provide the processing energy.




*Source:* Chalermthai, B., Giwa, A., Schmidt, J.E. & Taher, H. 2021. Life cycle assessment of bioplastic production from whey protein obtained from dairy residues. *Bioresource Technology Reports*, 15, 100695. https://doi.org/10.1016/j.biteb.2021.100695

textiles, wool does not release microplastics through wear and tear. As a biodegradable source of fibre, it constitutes an environmentally friendly alternative to synthetic materials, helping to reduce plastic pollution.

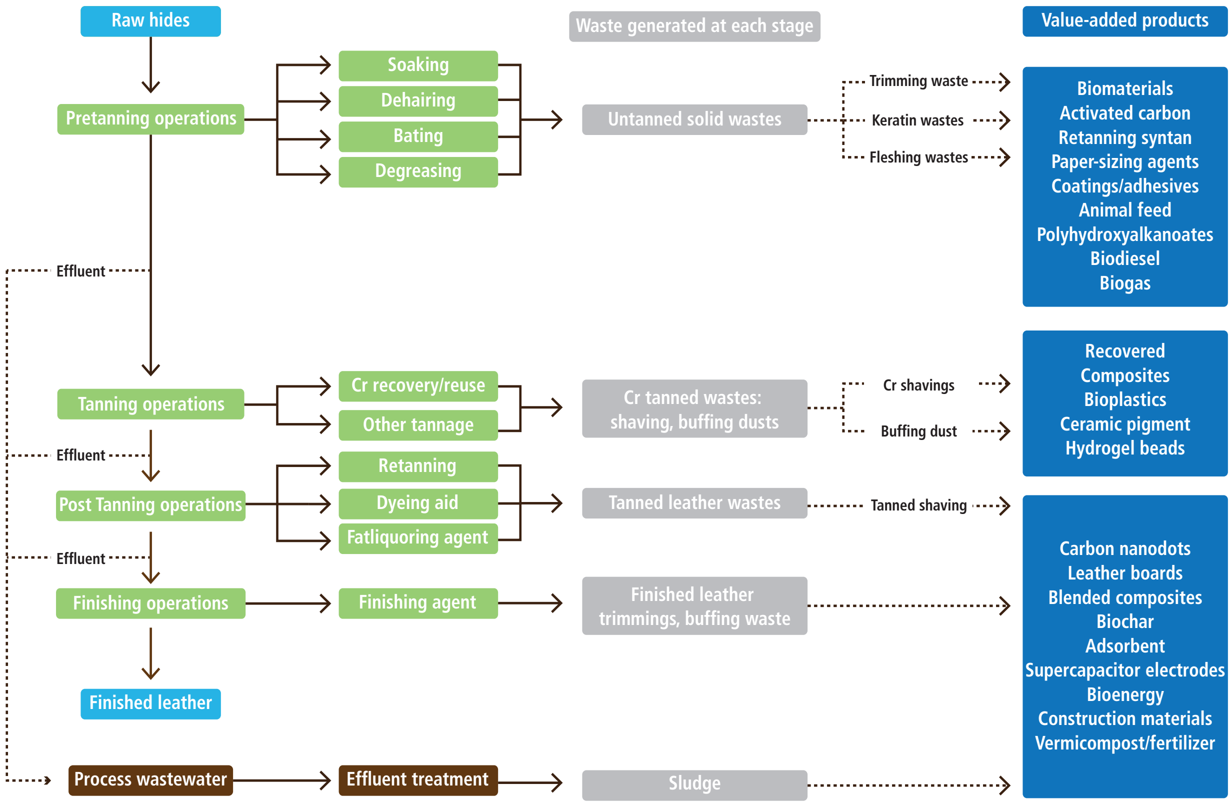
## 3.2.4 Hides and skins

### *3.2.4.1 Products and potential upcycling*

Leather is the main product produced from raw hides (of larger animals) and skins (of smaller animals such as sheep and goats), which are further processed worldwide into high-value products, including footwear, clothing, bags, furniture, car upholstery and many other items of everyday use (Kılıç *et al.*, 2023). The value of the global leather trade is in the order of USD 100 billion per year.

The leading exporters of hides and leather – in descending order of value – are the United States of America (25 percent of the total), Australia (8 percent), France (7 percent) and Germany (6 percent). However, the top exporter of processed leather goods in terms of value is China (30 percent), followed by Italy (20 percent) and France (15 percent) (STATISTA 2023). The leather industry

FIGURE 9
**Diagram of the tannery production process with an emphasis on the waste produced during leather processing and production**




*Source:* Adapted from Muralidharan, V., Palanivel, S. & Balaraman, M. 2022. Turning problem into possibility: A comprehensive review on leather solid waste intra-valorization attempts for leather processing. *Journal of Cleaner Production*, 367, 133021. https://doi.org/10.1016/j.jclepro.2022.133021

is an important national export industry in countries such as Ethiopia (Pujari *et al.*, 2023) and Bangladesh (Milu *et al.*, 2022).

The process of transforming raw hides and skins (easily biodegradable materials) into a robust and fashionable product for diverse purposes produces vast amounts of organic-based waste. The solid waste from leather production, including trimmings, fleshings, shavings, buffing dust and keratin wastes, holds significant potential for upcycling within the sector (Voinitchi *et al.*, 2022). Figure 9 presents the different solid and liquid wastes generated from leather production and a range of potential upcycled value-added products.

Recycling techniques can produce value-added products from the leather industry waste. For instance, buffing dust can be used to fabricate composite sheets and end product in the footwear production (Hashem and Nur-A-Tomal, 2018). Furthermore, buffing dust is a promising alternative to sand in concrete blocks (Pujari *et al.*, 2023) and to clay in brick production (Milu *et al.*, 2022). The collagen protein hydrolysate obtained from leather has been used as a fire-retardant additive in gypsum plaster (Voinitchi *et al.*, 2022). Similarly, Vidaurre-Arbizu *et al.* (2021) showed the potential of using buffing dust and shavings waste in the production of acoustic panels for the construction sector.

With the Cr tanning system, the hides get a blue tone from the Cr bath. Following this process, an irregularly shaped piece of wet blue leather is reduced into small cuts named "wet blue splits", which contain high levels of protein and chromium (Kennedy *et al.*, 2018). The Cr is normally extracted from the wet blue splits to be reused in the tanning process, whereas protein fractions are isolated from the splits and used in poultry diets as a substitute to SBM (Muralidharan, Palanivel and Balaraman, 2022).

Promising studies suggest that wet blue leather solid waste could also be upcycled for use in supercapacitor electrode production (Kennedy *et al.*, 2018).

In addition to solid waste directly produced during the tannery operations, large amounts of tannery sludge are generated from treated liquid wastewater effluent. The disposal of tannery sludge is an environmental concern since it normally contains high levels of Cr and organics. However,

TABLE 10
**Regional differences in the use of hide and skin-based products in Asia**

| High-income countries | Middle-income countries | Low-income countries |
|---|---|---|
| China, Japan and the Republic of Korea are major producers of leather.<br>China exported 10.23 million leather garments valued at USD 170 million, an 18.2% increase in volume and a 20.2% increase in value, respectively, compared to 2021 (Leather International, 2023).<br>Pig skin is also consumed in China as a snack. | South Asia, India, Bangladesh and Pakistan also play an important role in the global leather trade (Hira *et al.*, 2022). India accounts for around 13% of the world's production of hides/skins, generating 3 billion square feet of leather. Footwear accounts for most of the leather exports from India, with April–August 2022 exports valued at USD 1.8 billion (IBEF, 2023). In Bangladesh, the annual domestic supply of cowhides and skins (mainly from goats) is around 200 million square feet. Over 50 manufacturers produce various leather items for export (UN and ADB, 2016). | Afghanistan is one of the largest producers in the world of raw hides and skins from sheep and goats (UN and ADB, 2016).<br>Leather tanning and the production of leather footwear are the two main leather industries in Nepal. Wet blue leather accounts for most of Nepal's exports, while polished leather and leather footwear are mainly used domestically (UN and ADB, 2016). |

*Source:* See References.

Cr-rich tannery sludge can serve as a substrate for biogas production. Tannery sludge has also been repurposed as crop fertilizer using vermitechnology, a process in which earthworms speed up the breakdown of organic matter into compost (Muralidharan, Palanivel and Balaraman, 2022).

In Asia, hides and skins are used to make glue, sausage casings, rawhide, leather for shoes and bags, athletic equipment and cosmetics (Benjakul *et al.*, 2009) (Table 10). Hides and skins are also rendered to produce gelatin (Table 2). In addition, pork skins have medicinal uses, for example in dressing for burns, skin ulcers and skin grafting.

#### *3.2.4.2 Environmental risks, benefits and assessment*

Although leather is an upcycled product from the meat and dairy industry, raw skins and hides are subjected to extensive chemical, mechanical and biological processes, which require large amounts of water and energy (Joseph and Nithya, 2009; Kanagaraj *et al.*, 2015). The leather industry has faced pressure to regulate and minimize discharge to the environment. Studies estimating the GHG emissions from leather production have reported that the use of fossil fuels is responsible for the majority of emissions (Joseph and Nithya, 2009). Leather produced in countries with a high proportion of renewable primary energy, such as Brazil, New Zealand and Norway, have considerably lower GHG emissions. In these countries, the primary sources of GHG emissions from leather production are chemical use and solid waste (Kılıç *et al.*, 2023).

Cr tanning is the most widespread method of leather production, and is responsible for most of the GHG emissions (Chen, Lin and Lee, 2014), besides having a negative impact on soil and water quality. Strategies to decrease GHG emissions and other environmental impacts from tannery processing thus include the recovery and reuse of Cr as well as the replacement of conventional Cr tanning by wet white (Cr-free) tanning systems (Kanagaraj *et al.*, 2015). However, implementing wet white tanning does not always offer environmental benefits over conventional Cr tanning (Shi *et al.*, 2016). The use of organic tanning agents leads to greater wastewater disposal and energy consumption, and the wet white tanning process takes longer (Shi *et al.*, 2016).

### 3.2.5 Egg processing

#### *3.2.5.1 Products*

Laying hens are reared primarily to produce eggs for human consumption. Two main co-products are generated in the process: manure (Section 3.3) and spent hens at the end of their laying cycle. Spent hens may be used for meat production or rendered (Section 3.2.1). Eggs are sold either intact or in liquid form, with approximately 30 percent of those in liquid form used by the food industry (e.g. pasta, pastries). After breaking, the egg is separated from the shell, which becomes a co-product of egg production. The liquid egg – white and yolk – is either used as is, dried or frozen. Depending on the market, excess albumen or excess yolk may be available as a source of protein (albumen) or fat (yolk).

The eggshell is the egg's outer membrane, protecting egg contents and allowing for gaseous exchange. It is composed of the shell itself and of various internal membranes that surround the albumen. The eggshell consists of 94 percent calcium carbonate, while the internal membranes are approximately 11 percent polysaccharides, of which a third is mostly chondroitin sulphate A and B, 3 percent fat and 70 percent protein (Leach, 1982; Owuamanam and Cree, 2020). The organic matter can be removed from the eggshell by treating it with sodium hydroxide – a process known as calcinating (Faridi and Arabhosseini, 2018) – or by separating it from the eggshell for further isolation of valuable components (Ponkham, Limroongreungrat and Sangnark, 2010). Assuming full recovery of eggshells from liquid egg production, Owuamanam and Cree (2020) estimated the potential calcium carbonate yield across various regions. Based on their evaluation, using the entire eggshell production could potentially generate 2 million tonnes of calcium carbonate annually. From an animal nutrition perspective, eggshells thus have the potential to replace limestone – a mined source of calcium carbonate – in livestock diets.

The eggshell membrane protein is composed of structural protein (i.e. collagen and keratins) and of proteins or peptides with a high nutritional value, such as lysozyme, ovotransferrin, ovalbumin, globulin, ovomucin and defensin (Makkar *et al.*, 2015). These latter proteins and peptides contribute to the maintenance of a healthy digestive tract and can improve the digestibility of diets. In a trial with chickens, Makkar *et al.* (2015) demonstrated that the inclusion of 0.2 or 0.4 percent of eggshell membrane in the diet increased growth performance. They also noted an increase in the concentration of Immunoglobulins IgM and IgG in the plasma of birds, which is indicative of improved immune status, while lower cortisone concentrations suggested a reduction in stress levels. Similarly, Erisir *et al.* (2020) demonstrated that, in heat-stressed quails, the addition of 2 percent of eggshell membrane to the diet improved their oxidative status. In addition, the quails gained more body weight during the trial than those on a standard diet without eggshell membrane (Erisir *et al.*, 2020).

#### *3.2.5.2 Environmental risks, benefits and assessment*

As a co-product of the liquid egg industry, the use of eggshell and its membrane reduces landfill waste and the risk of environmental pollution through improper disposal. Eggshells adsorb various chemicals and heavy metals in soil. They have been successfully used in water and soil bioremediation (Oke *et al.*, 2014). The use of eggshells can also reduce the dependence on limestone for neutralizing acidic soils (Owuamanam and Cree, 2020).

#### *3.2.5.3 Energy (biofuels, electricity) and other uses*

Eggshells may be used to produce biodiesel, acting as a catalyst for the transesterification of fatty acids (Faridi and Arabhosseini, 2018). As a heterogeneous catalyst in biodiesel production, eggshells offer advantages over homologous catalysts: they are recyclable, do not corrode equipment and facilitate separation and purification steps (Faridi and Arabhosseini, 2018). Moreover, eggshells and eggshell membranes can be used to remove heavy metals from water (Faridi and Arabhosseini, 2018), serve as a substitute for limestone in cement (Veerabrahmam and Prasad, 2021), be processed into hydroxyapatite for use in medical and dental applications (Faridi and Arabhosseini, 2018), and contribute to the production of various polymers (Owuamanam and Cree, 2020). Extracted membrane collagens, combined with chondroitin sulphate and hyaluronic acid, are used medicinally as joint supplements. In addition to various biochemical, pharmaceutical and cosmetic applications (Aina *et al.*, 2022), eggshell membranes can also be used to produce collagen and gelatin (Table 2).

#### *3.2.5.4 Constraining factors*

Most of the eggshells from the production of industrial liquid eggs can be collected in egg breaking centres, although no system exists for the collection of eggshells from other sources (i.e. restaurants, retail or homes). At present, industrial eggshell products are considered to be hazardous waste in the European Union and the United States of America (Owuamanam and Cree, 2000). In Africa, most of the eggs are produced in local and backyard farms, with no biosecurity and poor market viability limiting industrial processing (Ajakaiye, Ayo and Ojo, 2010).

### 3.2.6 Aquaculture/fisheries processing for feed use

Fish processing generates co-products such as heads, viscera, skin, bones, scale and exoskeletons, accounting for approximately 30–70 percent of total aquatic production (Naghdi *et al.*, 2024). The leftovers from processing are commonly referred to as fish by-products. In the context of these guidelines, the term fisheries and aquaculture co-products will qualify materials derived from the processing of fish, crustaceans, shellfish, squids, bivalves, among other aquatic species. Fisheries and aquaculture co-products are mostly processed into fishmeal and fish oil and used as feed (Table 11; Kandyliari *et al.*, 2020). These co-products can also be transformed into various products such as fish silage, fishbone meal, shell powder, collagen, chitin, pigments (Table 12; Ramírez, 2013; Siewe *et al.*, 2019), and other products that provide humans with food and bioenergy.

In the past, fisheries and aquaculture co-products were often discarded, resulting in economic losses and environmental concerns. Today, however, fish waste is increasingly being transformed into food and non-food products. As ABPs, fisheries and aquaculture co-products are mainly being used as feed, thanks to their high-quality protein content. The development of new processing technologies has made it possible to convert materials once considered waste into valuable products safe for use in feed. Applying processing technologies to traditionally inedible parts of fish can convert these into highly nutritious products, improving the use of fish resources. According to Newton *et al.* (2023), there has been a growing interest in improving the use of fisheries and aquaculture by-products in the aquaculture sector.

#### *3.2.6.1 Fish co-products as feed*

Fishmeal is a dried meal made from the milling and drying of fish and fish parts. It can be derived from the processing of whole fish (typically small pelagic species and by-catches) as well as by-products from fish processing plants (fish offal and trimming). Despite the name, fishmeal can also include by-products from crustaceans, molluscs or other aquatic invertebrates. As a feed ingredient, fishmeal is

TABLE 11
**Typical rendered products from the aquaculture and fisheries industries**

| By-products | Description |
|---|---|
| **Protein meals** | |
| Fishmeal | Common feed source used in aquaculture and livestock production in many countries. It is composed of ground and dried fish and trimmings. Fish and fish trimmings are cooked and pressed to separate water and oil. The resulting material is then dried and milled to a desired particle size.<br>Fishmeal is rich in protein, omega-3 fatty acids and essential nutrients. |
| Fish silage | Liquid product made by fermenting fish offal and trimmings. It is used as a protein-rich feed for livestock and aquaculture species. |
| **Rendered fat** | |
| Fish oil | Produced similarly to fishmeal. The oil is an excellent source of omega-3 fatty acids. It is used in dietary supplements, pharmaceuticals and animal feeds. |
| **Mineral sources** | |
| Fish-bone meal | Produced from fish frames. It is composed mainly of minerals, and is high in calcium (Ca) and phosphorus (P) content. |
| Shell powder | Produced from crustacean shells. It is composed mainly of minerals, and is high in Ca and P content. |

*Source:* Ramírez, A. 2013. *Innovative used of fisheries by-products.* GLOBEFISH Research Programme. Vol. 110. Rome, FAO. [Cited 30 June 2025]. https://www.proquest.com/scholarly-journals/innovative-uses-fisheries-products/docview/1782996908/se-2

TABLE 12
**Higher-value products derived from the fish-rendering industry co-products**

| Co-products | Description |
|---|---|
| Collagen | Structural protein found in various fish tissues. As with livestock processing (Table 2), collagen can be extracted from fish co-products and refined into gelatine. |
| Chitin | Natural polymer, similar to cellulose, although it contains nitrogen. The partial deacetylation of chitin by either chemical or biological processes produces chitosan. Both chitin and chitosan are biodegradable and play a role in fat absorption, thus reducing plasma cholesterol. Crustaceans are currently the main source of chitin in commercial use. |
| Pigments such as astaxanthin | Extracted from crustacean shells and exoskeletons. they can be used in feed as a source of pigment, a biological antioxidant or a vitamin A precursor. |
| Leather | Fish skin is processed and used to produce leather goods, such as shoes, wallets and belts. |
| Protein hydrolysates | See Table 2. |

*Source:* Siewe, F.B., Akouan Ekorong, F.A., Karkal, S.S., Cathrine, M.S.B. & Kudre, T.G. 2019. Green and innovative techniques for recovery of valuable compounds from seafood by-products and discards: A review. *Trends in Food Science & Technology*, 85, 10–22. https://doi.org/10.1016/j.tifs.2018.12.004 and Koide, S.S. 1998. Chitin-chitosan: Properties, benefits and risks. *Nutrition Research*, 18(6): 1091–1101. https://doi.org/10.1016/S0271-5317(98)00091-8

appreciated for its palatable qualities, especially in aquaculture and feline pet food diets. The properties of fishmeal vary according to the species of fish that comprise the raw material (Ockerman and Basu, 2014).

Fishmeal, with its excellent amino acid profile and palatability, is considered an important ABP protein source. Currently, 87 percent of global fishmeal and 74 percent of fish oil (FO) production is used in aquaculture. A smaller proportion of global fishmeal is used to feed pigs (7 percent) and poultry (1 percent), with around 4 percent going to the pet food industry (Majluf *et al.*, 2024). According to the *OECD–FAO Agricultural Outlook 2022–2031* projections, the global fishmeal market is expected to grow over the next decade. The increasing share of fishmeal derived from fisheries and aquaculture co-products is the main driver, reflecting the sector's increased capacity to make use of these resources. Sandström *et al.* (2022) concluded that nearly all whole fish currently used to produce fishmeal and fish oil could be replaced with by-products.

The volume of capture fisheries processed into fishmeal and fish oil declined from over 30.1 million tonnes in 1994 to 17.2 million tonnes in 2020, while the share of fisheries and aquaculture co-products in global fishmeal production rose from 25 percent in 2010 to 34 percent in 2022 (FAO, 2024b). This goes to show that the sector is positively contributing towards the circularity of the fishing industry.

Although fishmeal can be produced from different sources, its quality depends on the freshness of the raw material and the processing method. In fact, manufacturing higher-quality products has enabled some producers to lead the market and command significantly higher prices per kilogram. The amount of ash, oil and protein in the final product is influenced by the raw materials. Poor-quality raw materials and poor processing, especially over-drying, can significantly reduce the nutritional quality of fishmeal. The proportion of bones in the meal will affect how much protein is included in feed. Fishmeal from by-products tends to have a higher proportion of fish bones than fishmeal from whole fish, resulting in a fishmeal with a higher ash level. Once considered inedible, fishmeal has undergone a remarkable transformation.

Improvements in processing technologies have made fishmeal and fish oil from by-products appealing to the market, partly because of their lower carbon footprint and contribution to circularity. However, further research is needed to assess the carbon footprint of fishmeal and fish oil production both from fisheries and fisheries/aquaculture co-products to better understand the different biogeochemical impacts of each source. In addition, incorporating traceability into the process is essential to ensure adequate biosecurity.

During fishmeal production, the cooked fish is pressed, resulting in a solid and a liquid phase. The liquid phase can be further subdivided into oil, aqueous and solid fractions. The demand for fish oil both as a feed ingredient and for direct human consumption is rising with the increasing knowledge of its health benefits. The annual fish oil output has remained stable at around 1 million tonnes, despite the growing use of fisheries and aquaculture co-products in fishmeal processing. Rich in long-chain omega-3 fatty acids (eicosapentaenoic acid and docosahexaenoic acid), fish oil is a valuable food and feed ingredient. Oil in fish feeds is increasingly being replaced by vegetable oils as the cost and demand for fish oil is increasing. The omega-3 fatty acids found in natural vegetable oils are shorter and known to have fewer beneficial health properties compared to those derived from fish. Alternative oils rich in long-chain omega-3 fatty acids, which are essential for livestock, are needed to produce optimal, healthy aquaculture products. Microalgae can be an alternative source of omega-3 fatty acids. Vegetable oil rich in omega-3 fatty acids usually contains alpha-linolenic acid, a short-chain version of omega-3. A new canola variety has also been bioengineered to produce high levels of eicosapentaenoic acid and docosahexaenoic acid rather than alpha-linolenic acid, resulting in an oil similar to that found in fish (Betancor *et al.*, 2015).

Fish silage consists of minced inedible fish products or whole fish, along with an added preservative to stabilize the mixture (FAO, 2024b). More often than not, the preservative used is a concentrated organic acid such as formic acid. When organic acids are not readily available, a fermentable carbohydrate or a lactic acid producing bacterial starter culture can be added instead to the minced fish. The bacterial culture will produce organic acid (lactic acid) and lower the pH of the minced fisheries and aquaculture co-products. Active at acidic pH, proteolytic enzymes – primarily from fish guts but also from bacterial cultures – hydrolyse proteins into peptides and amino acids. This generates a liquid solution rich in low molecular nutrients and, depending on the raw material's fat content, an oil fraction (FAO, 2024b).

Fish silage is ideal for small-scale processing units, where investing in a fishmeal plant is not economically viable. The product can be preserved for long periods and, as a liquid, it can easily be pumped into storage tanks for transport.

To ensure proper ensiling, the raw material must be minced and mixed with fruit waste or another source of sugar and inoculated with an acid-producing bacteria. The final mixture should have a pH of around 4.4 to prevent the growth of spoilage bacteria. At this pH, proteases from fish tissues and the lactic acid producing bacteria will hydrolyse proteins, resulting in a highly nutritious liquid product.

Any whole fish or parts of a fish can be used for fish silage. In most cases, fisheries and aquaculture co-products generated through fish processing will be the most appropriate raw material for silage production. The fish viscera (guts) should preferably be included to ensure that sufficient proteases are present to hydrolyse proteins in minced by-products. Ensiling should be undertaken as soon as possible after the fish has been processed. High-quality silage can only be made from high-quality raw materials (FAO, 2024b).

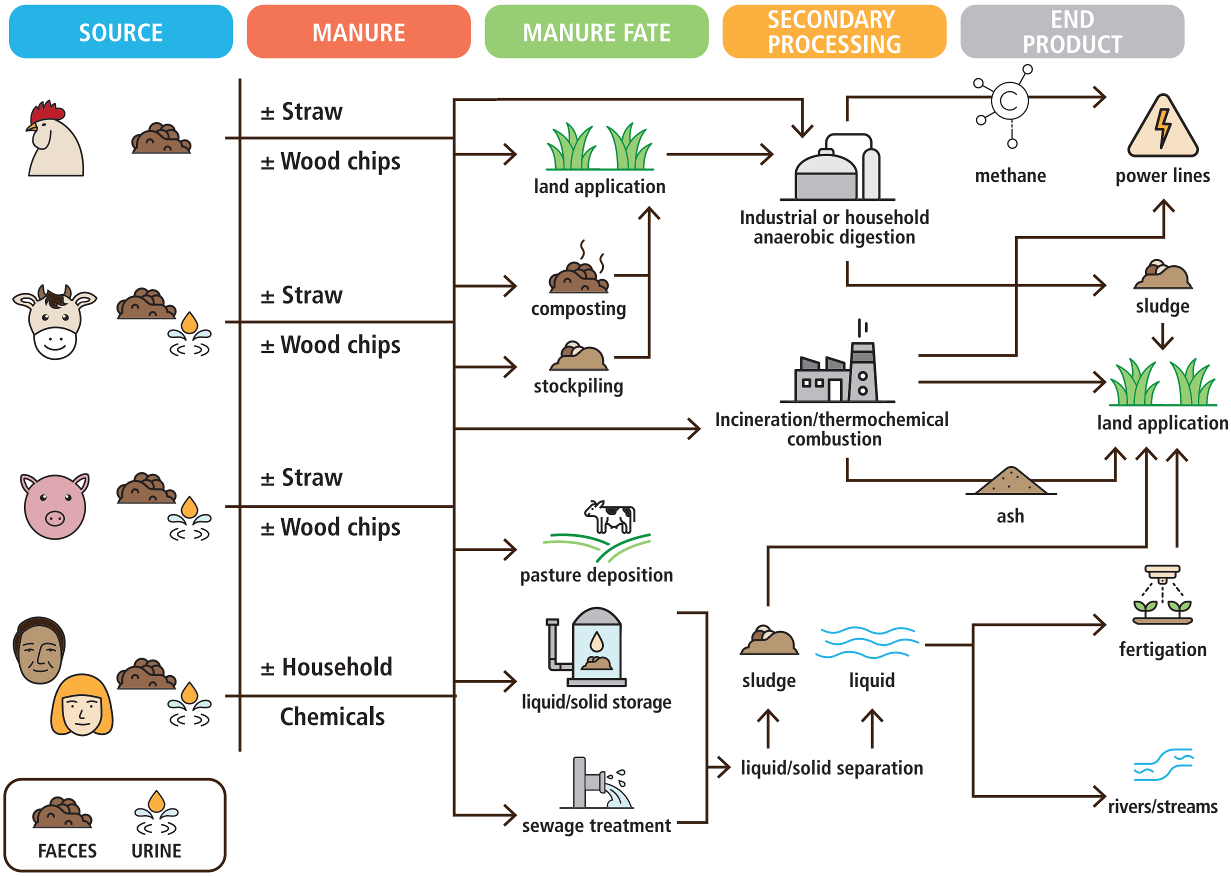
Fish silage can also be used as fertilizer if the raw material is of lower quality. Organic acids in fish silage act as a preservative and their antibacterial properties can be of benefit to feed livestock (FAO, 2024b). Fish silage has been successfully incorporated into the diet of pigs, resulting in higher growth rates, improved health and reduced mortality. Alternatively, fish silage can also be mixed with other feed ingredients, such as grains. Following the inclusion of fish silage, the total mixed ration can be fed directly to livestock as a wet feed.

It is recommended that fish silage should partially replace fishmeal or other protein sources in feeds. Its hydrolysed proteins mean that fish silage has a high level of free amino acids and peptides, which have been shown to improve the growth performance of some livestock species. While the use of fish silage for extruded feeds is well documented, fish silage can also replace fishmeal (typically 5 to 15 percent of the total fishmeal content) and adds water to the feed mixture prior to extrusion. The inclusion of silage has also been shown to produce pellets that are stronger and more resistant to physical disruption, reducing waste during transport and feeding (FAO, 2024).

#### *3.2.6.2 Nutritional value of aquaculture and fisheries co-products*

Fishmeal contains proteins ranging from 60 to 63 percent for standard quality, and up to 67 percent for premium quality (Ramírez, 2013). Various qualities of fishmeal are produced and the availability of protein may be impacted by processing procedures such as ensiling or rendering. High-quality meals, typically produced at low temperatures for higher digestibility, are commonly incorporated in fish and piglet feeds. Prime-quality meals have a wide range of applications, while lower quality meals are primarily

FIGURE 10
**Manure management and production of bioenergy and biofertilizer co-products from livestock manure and post-consumer wastes**




*Source:* Authors' own elaboration.

used as ingredients for pigs, poultry and dairy cattle feed (Ramírez, 2013).

Fish oil, as a rich source of long-chain omega-3 fatty acids (eicosapentaenoic acid and docosahexaenoic acid), is a valuable food and feed ingredient.

Fat-free silage will generally have a moisture level close to 80 percent, a protein level of approximately 15 percent and an ash level of less than 4 percent. If a drier product is required, the silage may be evaporated (FAO, 2024)

### *3.2.6.3 Environmental risks and benefits*

Using by-products from the filleting industry reduces the reliance on fishmeal and fish oil produced from over-fishing or fishing given fish species, thereby preserving natural resources. Moreover, fish feed waste and faeces generated by intensive fish farms can pollute surrounding waters and the seabed, resulting in degraded water and sediment quality. Chemicals and pesticides used in some fish farming operations to control parasites and infectious diseases can also contaminate and impact surrounding marine life.

### *3.2.6.4 Constraining factors*

Because fishing and harvesting are seasonal, the availability of by-products from the fish processing industry varies throughout the year, with quality varying according to the type of fish or seafood being processed. Risks of off-taste and off-flavours in meat/egg/milk products also need to be considered when fisheries and aquaculture co-products are used as feed (Ramírez, 2013).

## 3.3 MANURE MANAGEMENT AND POST-CONSUMER WASTES

This section aims to describe the current options for managing solid and liquid excrement streams generated across the livestock supply chain, and the technologies that enable these materials to be used as organic fertilizers and/or generate new co-products (bioenergy and biofertilizers). This includes manure management at the-cradle-to-farm-gate stage (e.g. manure, on-farm wastewater, sludge), as well as post-consumer waste management (e.g. wastewater and sewage solids) (Figure 10). This chapter considers both livestock excreta and human-derived excrement sources for two reasons. First, solid and liquid excrements from both sources pose environmental risks, ranging from biological and chemical hazards – such as pathogen presence and GHG emissions – to uncontrolled nutrient release into the environment (Pepper, Brooks and Gerba, 2019). Second, solid and liquid excrements from livestock and human sources can follow similar circular bioeconomy pathways and technologies, enabling the safe reintegration of materials into livestock and food production systems by producing organic fertilizers, renewable energy and soil amendments. Manures, effluent, wastewater and human sewage sludges are often stabilized and then reapplied to agricultural systems as soil amendments or biofertilizers because of their nutrient and/or carbon value (Pepper, Brooks and Gerba, 2019). Solid and some liquid excrements can be processed using a range of technologies to produce power and heat (Appels *et al.*, 2011). In addition, solid or liquid by-products from bioenergy processing, such as digestate from AD or biochar from pyrolysis, may also have beneficial properties, including as soil amendments or biofertilizers (Khoshnevisan *et al.*, 2021).

This section has three subsections. Subsection 3.3.1 outlines the general characteristics of livestock excreta and post-consumer waste, namely the estimated global volumes of production, its general composition and the processes involved in manure management (e.g. collection, storage, treatment and processing, and land application). Technologies for managing emissions are also described. Post-consumer streams, particularly wastewater and sewage sludges, and their treatment processes and general characteristics are then summarized. Subsection 3.3.2 presents common bioenergy technologies, including AD and thermochemical processes, which can generate power and/or heat from livestock excreta or post-consumer waste inputs. Lastly, subsection 3.3.3 examines bio-based fertilizer and soil amendment processes and technologies that can be used to stabilize and recover or recycle nutrients and carbon derived from livestock and post-consumer waste inputs. These include composting, nutrient recovery methods and emerging biotechnologies such as vermicomposting. Such processes are essential for ensuring that resources from the livestock supply chain can be safely reintegrated into the food production system by providing nutrient inputs for feed crops and pastures.

### 3.3.1 Description of residue streams

#### *3.3.1.1 Manure management*

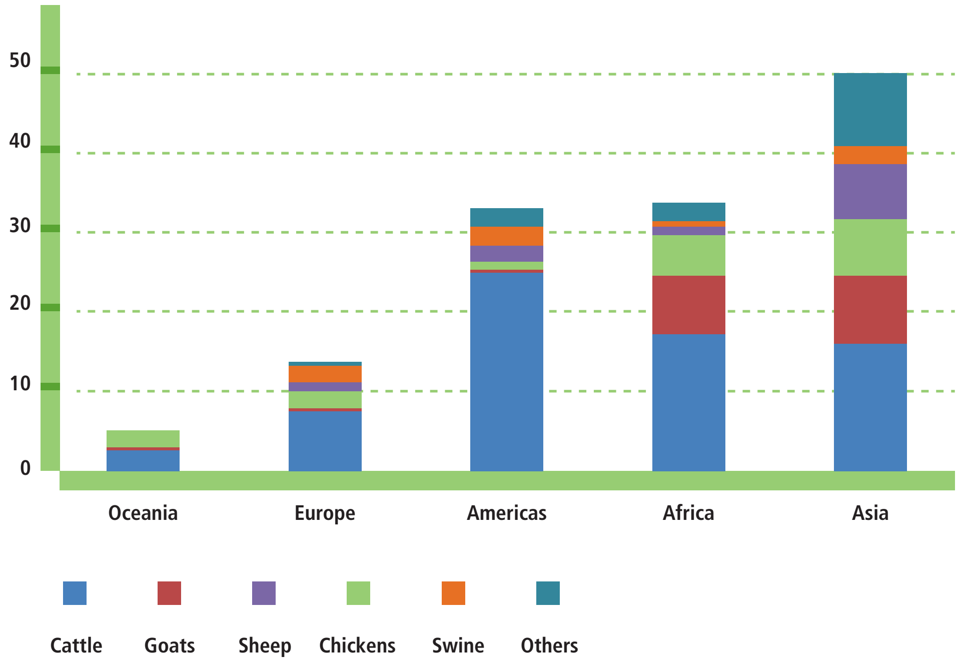
Nutrient management is central to agricultural production and food supply chains. Effective manure management is also critical for protecting the environment against threats such as eutrophication and water pollution caused by nutrient (largely N and/or P) runoff or leaching, as well as air pollution from $NH_3$, GHG emissions ($CH_4$ and nitrous oxide) and unpleasant odours (Menzi *et al.*, 2010). Since the early twentieth century, manure management has driven the development of agricultural practices such as manure recycling, crop residue management and the application of mineral fertilizer (Sutton *et al.*, 2022; Erisman *et al*., 2008; Gerber, Uwizeye and Schulte, 2014). Livestock can help transfer and convert PBPs (e.g. grass or co-products, rangelands, food residuals and food loss) into ASFs (Leip *et al.*, 2019; Van Zanten *et al.*, 2018). Livestock require nutrients such as N and P for growth, development and function, but most nutrients are excreted via urine and faeces, which can be recycled and reused. From a circular bioeconomy perspective, manure can be a valuable source of plant nutrients, particularly N and P, which can be returned to soils in place of mineral fertilizers. Manure can also be an excellent source of micronutrients and organic matter, which improve soil health (Kao *et al.*, 2020). However, additional organic matter can also reduce the uptake of minerals such as selenium (Kao *et al.*, 2023).

The impact of manure on soil health and productivity, such as increasing organic matter content and improving soil water retention, is often difficult to quantify and varies widely depending on soil type and past soil management practices. Technologies such as the generation of biogas can also be applied to harvest energy from manure and other inputs, while producing sludge as soil amendment, besides other co-products.

Manure management involves the collection, storage, treatment and utilization of animal manure. Best practices in those areas can deliver multiple environmental, economic and health benefits, with important implications for farm productivity and the bioeconomy (Kupper *et al.*, 2015; Menzi *et al.*, 2010). However, nutrient losses present multifaceted problems, affecting air, water, human health, climate, biodiversity and the wider economy. The United Nations Economic Commission for Europe (UNECE) has recently adopted a *Guidance Document on Integrated Sustainable Nitrogen Management* that outlines the principles and opportunities of N management, including manure. Although the nutrient value of manure has long been recognized, the ease of use and low cost of manufactured mineral fertilizers have led to their widespread use in many industrialized countries (Powell *et al.*, 2010). The aim of integrating sustainable N management into livestock systems is to reduce N losses to the environment, thus helping to protect human health, the climate and ecosystems, while ensuring sufficient food production and improving N use efficiency through appropriately balanced N inputs.

The quantity, quality and properties of manure depend on the animal species as well as feeding, rearing and manure management practices. The highly variable manure composition reflects the diversity of livestock production

FIGURE 11
**Quantity of manure produced by region (million tonnes of N)**




*Source:* Authors' own elaboration, based on data sourced from FAO. 2016. In: *FAOSTAT:* Global protein consumption indicator. [Accessed on 19 July 2025]. https://www.fao.org/faostat/en/#data/EMN Licence: CC-BY-4.0.

systems, which are shaped by climate, geography, culture and economics. The estimated volume of manure production is expressed in terms of N and sometimes P flows. In 2018, the total global production of livestock manure was estimated at 125 million tonnes of N (FAO, 2020), of which 7 million tonnes were lost, mainly as $NH_3$. In 2018, manure deposited on pastures was estimated at 88 million tonnes N, with between 3 and 9 million tonnes deposited in grazing systems in Brazil, China, India, Ethiopia and the United States of America (FAO, 2020). Manure land applications were estimated at 27 million tonnes N, with 3 million tonnes of N used for other purposes (heating and construction). The quantity of manure N produced in various regions of the world (Figure 11; FAO, 2023b) reflects the distribution of livestock, estimated at 25.8 billion chickens, 1.3 billion sheep, 1.5 billion cattle, 1.1 billion ducks, 1.1 billion goats, 1 billion pigs, 205 million buffaloes and 60 million horses (FAO, 2023b).

Livestock pressure on land – livestock unit per agricultural land area – is highest in countries with relatively low agricultural land areas but high livestock numbers (FAO, 2020). For example, estimated figures were higher for Singapore and China (52 and 11 livestock units/hectare, respectively) compared to 0.2–3.4 livestock units/hectare for the European Union (FAO, 2020; EUROSTAT, 2023). High-density livestock systems can also result in the accumulation of manure and nutrients within a limited geographical area because of a lack of sufficient agricultural land available for manure application and high transportation costs for other regions.

Manure composition can pose challenges for agricultural or land application. Manure tends to have lower nutrient concentrations compared to mineral fertilizers, different nutrient ratios (N:P, C:N) and a greater proportion of slower release forms of N and P (as a result of associations with organic matter). Manure may also contain contaminants such as heavy metals, pharmaceuticals and pathogens, which must be managed (Vaishnav *et al.*, 2023). The nutrient content of raw and processed manure varies between different livestock production systems, as ruminants, pigs and poultry differ in their nutritional requirements for crude protein and energy, feed conversion efficiencies and manure excretion pathways (Leip *et al.*, 2019). Manure treatment processes can also alter nutrient concentration, ratios and plant availability (Lamolinara *et al.*, 2022). Manure may not always have the ideal characteristics to both meet balanced nutrient requirements for crops and minimize emissions during application. In particular, the high DM and carbon content can cause problems during slurry storage, application and use for crops. High-moisture manures present a higher risk of generating $CH_4$ during storage because of the presence of degradable carbon under anaerobic conditions. Prior to land application, slurries must be homogenized to disrupt the surface crust and to suspend sediments. Homogenization can be energy intensive and increase $NH_3$ emissions by increasing the exposure of slurry to the atmosphere (Sutton *et al.*, 2022). During land application, slurries should be applied below or near the soil surface to reduce $NH_3$ emissions. Liquid manure with high DM content shows slower soil infiltration as a result of higher viscosity, which may then increase $NH_3$ emissions. Following land application, high DM content drives the microbial immobilization of N, limiting its immediate availability to plants or delaying its release until after crop yields have already been affected. In addition, increased soil N concentrations have been shown to increase rates of nitrification and denitrification, increasing nitrous oxide ($N_2O$), nitrogen oxides (NOx) and nitrogen gas ($N_2$) losses (Dosch, 1996). As a result, it may be beneficial to reduce slurry DM and carbon content at an early stage of manure management. Efforts are ongoing across the European Union to develop manure processing technologies that would make this valuable agronomic resource safe to use.

Manure collection methods depend on the livestock production system. Slurries, solid manure or droppings are produced depending on the livestock housing system. A "slurry" or "liquid manure" is produced when DM content ranges between 1 and 10 percent, allowing it to flow by gravity and be pumped through distribution systems (Pain and Menzi, eds, 2011).

"Solid manure" has a DM content of more than 10 percent and it cannot flow with gravity or be pumped, but it can be stockpiled or composted (Pain and Menzi, eds, 2011). Livestock housing conditions can improve environmental performance and limit nutrient losses by reducing indoor temperatures, emitting surfaces and soiled areas, and air flow over these areas (Sutton *et al.*, 2022). The use of additives such as acids can also be effective, especially when combined with management practices like the frequent removal of slurry to outside storage and separating liquid and solid components. Smart barns with optimized ventilation can improve conditions in open housing, while air scrubbing can be an optimal ventilation solution for closed housing systems.

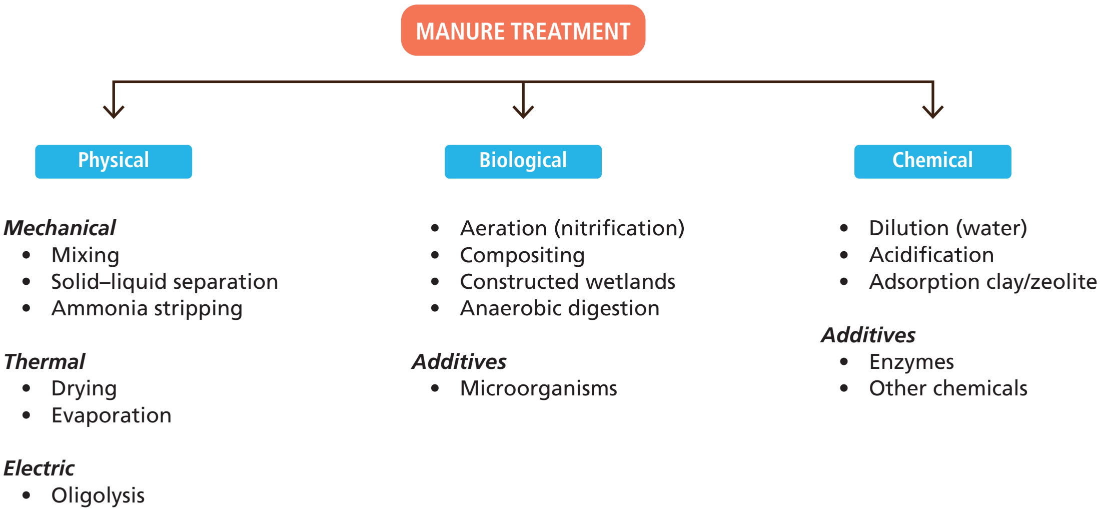
In confined livestock systems, bedding, feed losses and wash water can be added to the manure mixture. In confined cattle barns, manure and washings can be scraped from the floor into liquid storage tanks or lagoons (covered or uncovered) or washed directly into a pit under slatted floors. Pig and cattle manure is managed in both liquid and solid forms, with V-shaped scrapers used to move pig manure into pits below slatted floor housing (Likiliki, Convers and Beline, 2020). During grazing on pastures or grasslands, livestock deposit faeces and urine directly on the land. Care must be taken to avoid nutrient accumulation in high animal density areas, such as around water sources, and management practices should be followed to reduce defecation and urination directly into surface waters. In poultry, uric acid is mostly managed in a dry form, either directly as droppings or as a mixture with bedding. Dried or undried droppings may be collected in pits or on a belt that transports them outside the barn.

Liquid manure is mainly stored outdoors in covered or uncovered structures and transported by pumping or gravity. Manure storage structures can range from concrete pits and metal storage tanks to lagoons. In the European Union, solid manure is either applied directly to the land, stockpiled for up to a year or composted. The storage of manure processing co-products also follows the same guidelines. The EU regulations on minimum storage durations for manure are related to the growing period of crops to ensure that it is applied only when it can contribute to crop demand. The UNECE *Guidance Document on the Integrated Sustainable Nitrogen Management* lays out the principles of manure storage, treatment and processing:

> *For livestock agriculture to become sustainable, an optimal and efficient use of manure nutrients and organic matter is essential. However, manure N may be easily lost via gaseous emissions ($NH_3$, $N_2O$, NOx, $N_2$) and leaching of nitrate and other N compounds. Besides N losses, $CH_4$ emissions from manure to the atmosphere must be reduced as much as possible, to limit climate change impacts. Nitrate leaching and pollution of watercourses with N, P and organic compounds are possible if manures are not stored within impermeable barriers to prevent leakage of slurry or leachate from solid manures. Significant N losses may occur during storage of either urine, feces, or mixtures (slurries and farmyard manures/ deep litters), and simple treatment (e.g. solid–liquid separation) or more advanced processing (e.g. AD, ultrafiltration) may enable more appropriate manure management with lower N losses*
>
> **(Sutton et al., eds, p 71.)**

In the field of manure management, the UNECE *Guidance Document on Sustainable Nitrogen Management* identifies the following priorities for improved environmental performance and reduced nutrient losses (Sutton *et al.*, 2022): (a) store solid manures outside the barn on a solid concrete base in a dry/covered location; (b) ensure tight slurry stores, and cover either by a solid cover or by ensuring sufficient natural crust formation; (c) use manure treatment where relevant to (i) homogenize nutrient content for more even field spreading to ensure that all available nutrient resources are used effectively for crop growth; (ii) reduce slurry DM content through processes like solid–liquid separation to enhance soil infiltration and limit $NH_3$ loss; (iii) increase slurry ammonium ion content to maximize crop N availability; (iv) lower pH by acidification to reduce $NH_3$ volatilization and enhance fertilizer value; (v) apply manure treatment methods to enable combined energy and nutrient recovery (e.g. AD).

FIGURE 12
**Options for simple manure treatment**




*Source:* Amon, B., Stouman Jensen, L., Groenestein, K. & Sutton, M. 2020. Sustainable nitrogen management for housed livestock, manure storage and manure processing. In: R. Baines, ed. *Reducing greenhouse gas emissions from livestock production*, pp. 115–160. Cambridge, UK, Burleigh Dodds Science Publishing. https://doi.org/10.1201/9781003048213-5

Manure treatment and processing methods depend on the scale, intensity, specialization and the regional concentration of livestock (Bai *et al.*, 2021). Manure handling practices and use in the manure management chain (i.e. animal housing, storage of manure, treatment or processing operations, application) have changed over time as a result of increasing farm size and greater specialization and intensification. A decoupling of crop and livestock production often occurs, which leads to excessive manure production in livestock-dense areas. Treatment and processing of manure can be costly in terms of economic, environmental, and energy resources. Because of these costs, different options for manure handling should be evaluated with consideration of local limitations and regulations

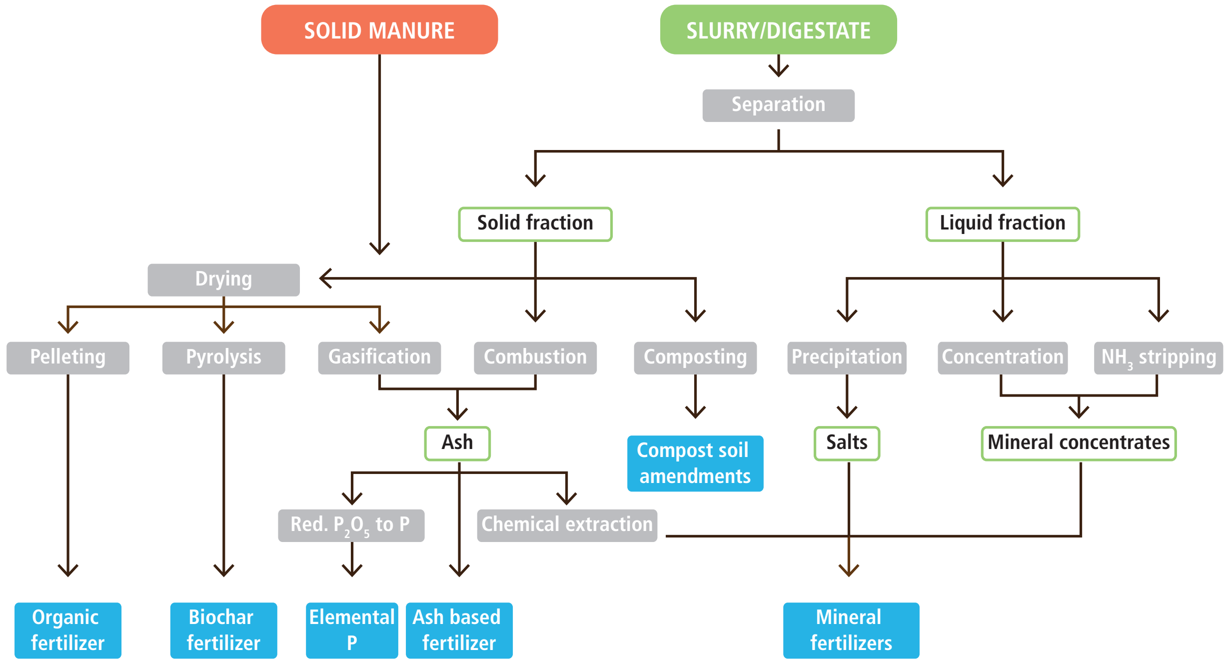
Treatment and processing of manure can use up considerable financial, environmental and energy resources. It is therefore important to evaluate manure handling options based on local constraints and regulations. Options for manure handling can be grouped into three categories: (a) direct land application; (b) simple treatment; and (c) advanced processing. Simple treatment and advanced processing may be most relevant when conditions favour overall environmental benefits (e.g. high livestock density, nutrient surplus for crops). These decisions should also avoid "pollution swapping", which would occur if reductions in $NH_3$ losses resulted in increased nitrate leaching (Sutton *et al.*, 2022). For example, fertigation – the irrigation of crops with liquid manure – can be used when the volume is sufficient and the nutrient profile matches crop requirements. However, modifications to manure management techniques are often required to avoid clogging drips or sprinklers (e.g. solid–liquid separation, stabilization tanks at farms).

Manure treatments are typically designed to improve physical and chemical properties such as fluidity (adding water or separating solids); stabilize volatile nutrients (acidification); and reduce odour (aeration). Granulation or pelleting can ease the handling, transport and application of manure. Single-stage treatments are typically applied on farms, near the site of livestock production. Treatment processes can be physical, biological or chemical (Figure 12), either alone or in combination. Slurries and liquid manure can undergo mechanical separation to isolate a solid fraction that is rich in organic N and P and a liquid fraction with low P but high N and K content. When selecting the treatment and processing technique, the following should be considered: homogenization to ensure even field spreading and improve crop nutrient availability; reduced slurry DM content (e.g. solid–liquid separation) to improve soil infiltration and reduce $NH_3$ losses; increased slurry ammonium ion concentrations to improve available crop N; acidification to lower $NH_3$ volatilization and increase fertilizer value; and, if possible, recovering both energy and nutrients (Sutton *et al.*, 2022).

Manure processing can transform a variety of manure types and sources into value-added products, usually through more complex and multistep processes. For example, in China, 80 percent of manure on large-scale farms was processed in 2019, of which 30 percent originated from pigs (Wei *et al.*, 2021). By comparison, the largest source of processed manure (23 percent) in the United States of America is from dairy cattle (FAO, 2020).

FIGURE 13

**Options for combining simple manure treatment with more advanced processes to upgrade nutrient and energy recovery**




*Note:* The displayed options result in widely different bio-based fertilizers. Only a few are currently applied at a commercial scale; others are still at the experimental/pilot stage (and are therefore not dealt with here).

*Source:* Amon, B., Stouman Jensen, L., Groenestein, K. & Sutton, M. 2020. Sustainable nitrogen management for housed livestock, manure storage and manure processing. In: R. Baines, ed. *Reducing greenhouse gas emissions from livestock production*, pp. 115–160. Cambridge, UK, Burleigh Dodds Science Publishing. https://doi.org/10.1201/9781003048213-5

Manure processing technologies may be located on farms or operated as centralized or decentralized plants, producing marketable products that can be used as fertilizers, soil amendments or secondary raw materials (Sutton *et al.*, 2022). Manure processing needs to occur within a distance that is economically viable for transport between farms and collecting plants (Lopez-Ridaura *et al.*, 2009; Khoshnevisan *et al.*, 2021; Sefeedpari *et al.*, 2019). Manure processing methods vary in relation to intensive vs extensive livestock production systems and the degree of nutrient accumulation from manure in regions known as hotspots (Bai *et al.*, 2022; Greenwood, 2021; Lassaletta *et al.*, 2019).

The transport of manure is often regulated (e.g. the EU Nitrate Directive), with treatment and processing often being used to facilitate manure handling and transport (Loyon, 2017). The primary aim of manure processing is to recycle N, P and other nutrients to facilitate their capture by the crop or for alternative uses (Jensen, 2013a; Sutton *et al.*, 2022). Moreover, the processing procedure can be linked to energy generation, while ensuring that it has a low-energy footprint (net energy production). Local manure processing solutions that minimize transport costs and emissions are preferred, unless regional processing improves efficiency thanks to economies of scale (Jensen, 2013a).

Advanced manure processing techniques that capture N and produce value-added nutrient products should be employed in situations where other options are unavailable. Some of these technologies are shown in Figure 13, although this list is not exhaustive. These include high-tech separation by filtration, reverse osmosis and $NH_3$ scrubbing. Ideally, the production of recovered, bio-based fertilizer products should be guided by demand rather than supply, reflecting their value to livestock or crop production. However, to achieve this, regional manure surpluses that often result from large-scale livestock operations must be dealt with (Sutton *et al.*, 2020). Land applications of manure are discussed in more detail in Section 3.3.3.

Various technologies can be applied at different points in the livestock value chain to mitigate the release of GHG and $NH_3$ emissions from manure. The following solutions have been primarily developed for, and are mostly used in, confined farming systems.

Established technologies include dietary modifications, such as reducing crude protein (CP) intake (Swensson, 2003; Sutton *et al.*, 2022), adding calcium salts to slurries (Kim *et al.*, 2004), supplementing the diet with benzoic acid to reduce urine pH in pigs (Murphy *et al.*, 2011) and increasing the non-starch carbohydrate content of livestock diets (Feilberg and Sommer, 2013). Increasing the frequency of manure removal and lowering slurry storage temperatures can also reduce $NH_3$ emissions (Cai *et al.*, 2015). Lowering barn temperatures and reducing air flow can cut emissions by up to 20 percent. This is achieved through optimized barn climate control measures such as roof insulation or automated natural ventilation systems (Monteny, 2000; Smits, 1995). The emissions of $NH_3$ can also be impacted by bedding, which can absorb urine and increase the bulk density of manure, lowering emissions by up to 50 percent (Gilhespy *et al.*, 2009). Among other strategies, slurry separation can reduce $NH_3$ emissions by up to 10 percent by limiting urea hydrolysis (Emmerling, Krein and Junk, 2020). During manure storage, covering manure or allowing it to form a natural crust can significantly reduce the release of both $NH_3$ and NOx.

Additions or modifications during manure storage can also significantly reduce GHG emissions by limiting the conversion of $NH_3$ into NOx. Acid scrubbers can be used to absorb dissolved $NH_3$ and produce an ammonium ion salt solution, while biofilters or biotrickling filters reduce $NH_3$ emissions through microbial activity (Nicolai and Lefers, 2006; Dumont *et al.*, 2020). The acidification of manure both in-house and during storage – either chemically or by means of bioacidification – can reduce $NH_3$ emissions by up to 77 percent (Kupper *et al.*, 2020). A combination of acidification and manure drying has been found to reduce $NH_3$ emissions by up to 94 percent (Morey *et al.*, 2023). Acidification, absorbents, urease inhibitors and bacterial cultures or enzymes can also be added to alter manure biodegradability (Van der Stelt *et al.*, 2007; Mažeikienė and Bleizgys, 2022). The addition of adsorbents such as clay/zeolite, biochar, peat, phosphogypsum, tannins and tannin-based polymers can reduce $NH_3$ losses. However, to be effective, large amounts of additives are often required (Webb *et al.*, 2005; Sepperer *et al.*, 2020).

Several new technologies have the potential to reduce GHG and $NH_3$ emissions. Physical technologies include pulse-combination drying, air $NH_3$ stripping and ceramic membrane distillation. Pulse combination drying can be used to dry solid manure after it has been separated from the liquid stream. Air $NH_3$ stripping can be applied after raising the pH of liquid manures or wastewaters to 10.5–11. A precipitation tank is used to capture phosphate salts and carbonates, if lime was used to increase the pH. About 87 percent of $NH_3$ can be recovered from digested pig slurries using this method (Provolo *et al.*, 2017).

Chemical technologies, such as plasma recovery, use electricity to split N and oxygen molecules so that they recombine to form reactive oxygenated N gas intermediates. These intermediates can then be absorbed into the liquid phase of slurries and digestates, making them available for plant uptake (Kumari *et al.*, 2018; Wu *et al.*, 2021). Biological technologies employing microorganisms such as microalgae or phototrophic purple bacteria (PPB) can also increase N capture. Microalgae can absorb a range of nitrogenous compounds to support photosynthesis, including $NH_3$, with capture rates of more than 95 percent in some cultures (Kang and Wen, 2015). Phototrophic purple bacteria have been shown to effectively partition carbon, N and P from the soluble to the solid phase of manure, enabling the concentration of nutrients from dilute manure streams (Hülsen, Batstone and Keller, 2014; Marazzi *et al.*, 2017). With high biomass yields, PPB can be used as a feed ingredient, a substrate for energy production through AD, a source of biofuel or as a biofertilizer (Coppens *et al.*, 2016; Dahiya *et al.*, 2018).

Post consumer streams, or wastewaters may originate from point sources, such as confined animal operations, food processing facilities and municipal sewage treatment plants, as well as from diffuse sources like contaminated surface runoff. Wastewaters may exhibit high chemical oxygen demand (COD) and biological oxygen demand (BOD), along with high microbial loads, suspended solids, strong odours and potential contaminants such as pathogens, heavy metals, pharmaceuticals and pesticides (Vaishnav *et al.*, 2023) (Table 13). Settling ponds and facultative lagoons are often used to reduce the risk of wastewater directly entering surface and ground waters. Constructed wetlands may also serve to gradually treat wastewater before it is released into the environment. The solids that settle out of the pond or lagoon system accumulate and are periodically removed by mechanical desludging. Depending on the animal production system, crop type, surrounding land use and season, wastewater can be applied to nearby agricultural land through fertigation.

Municipal wastewater treatment typically involves several stages: pretreatment (e.g. physical separation, sedimentation, coagulation); primary treatment (e.g. coagulation precipitation, flocculation), secondary treatment (e.g. biological degradation, filtration, adsorption); and tertiary treatment (e.g. oxidation, membrane filtration). Nutrients such as N and P are removed from the liquid phase through biological or chemical methods. It is estimated that, globally, wastewaters contain 16.6 million tonnes of N, 3 million tonnes of P and 6.3 million tonnes K. If recovered, these could offset approximately 13 percent of the global nutrient demand for agriculture (Qadir *et al.*, 2020).

Sludge management depends on the wastewater source. While N can be lost from the wastewater/sewage system through denitrification, other plant macronutrients (i.e. P, K, Ca, and magnesium [Mg]) and micronutrients (i.e. iron, manganese, zinc) remain in the sludge, along with heavy metals that can pose a risk to animals and humans. From an agronomic perspective, sludge can be challenging to apply without additional fertilizer supplementation because of its relatively low in N and high in micronutrient concentrations. The frequent removal of sludge from animal

TABLE 13
**Physico-chemical characteristics of sample wastewaters and sludge**

| Parameter | Dairy wastewater | Swine wastewater | Swine lagoon sludge | Poultry wastewater | Municipal wastewater |
|---|---|---|---|---|---|
| pH | 4.7–11 | 6.4–6.8 | 7.37 | 7.1–7.3 | 6–8 |
| COD (mg/L) | 10 000– 50 000 | 14 532–15 965 | 62 240 | 480–850 | 250–1000 |
| BOD (mg/L) | 40 000–48 000 | 5 806–8 451 | N/A | 0.39–0.74 | 110–400 |
| Total solids (mg/L) | N/A | 7 631–10 657 | 9% | 430–720 | N/A |
| TSS (mg/L) | 2.8 | 1 349–5 075 | N/A | N/A | 100–350 |
| TN (mg/L) | 14–830 | N/A | 3 940 | 56.5–70.7 | 20–85 |
| TP (mg/L) | 9–280 | 329–476 | 3 830 | 0.2–0.6 | 4–15 |
| TOC (mg/L) | N/A | N/A | 5 730 | N/A | N/A |
| Electrical conductivity (dS/m) | 1.87 | 9.88–10.99 | N/A | N/A | N/A |
| Bicarbonate (mg/L) | N/A | N/A | N/A | 326–434 | N/A |

*Note:* COD = chemical oxygen demand; BOD = biological oxygen demand; TSS = total suspended solids; TN = total nitrogen (N); TP = total phosphorus (P); TOC = total organic carbon (C).

*Source:* Vaishnav, S., Saini, T., Chauhan, A., Gaur, G.K., Tiwari, R., Dutt, T. & Tarafdar, A. 2023. Livestock and poultry farm wastewater treatment and its valorization for generating value-added products: Recent updates and way forward. *Bioresource Technology*, 382, 129170. https://doi.org/10.1016/j.biortech.2023.129170

processing lagoons and ponds, although more costly, may support sludge management over the lifetime of the storage basin. Water makes up 70–80 percent of sludge, even after physical dewatering. Other sludge processing techniques include drying, blending and granulation to overcome the barriers to transporting sludge over long distances. Treated sewage sludges are commonly referred to as "biosolids", which includes the cake produced from raw sludge following AD and dewatering, pelletization (further drying), lime amended biosolids (stabilization) or composting. Additional technologies, such as thermal treatment, can recover energy and potentially generate value-added chemicals, materials or soil amendments, while reducing the land footprint required for application and the weight of materials transported.

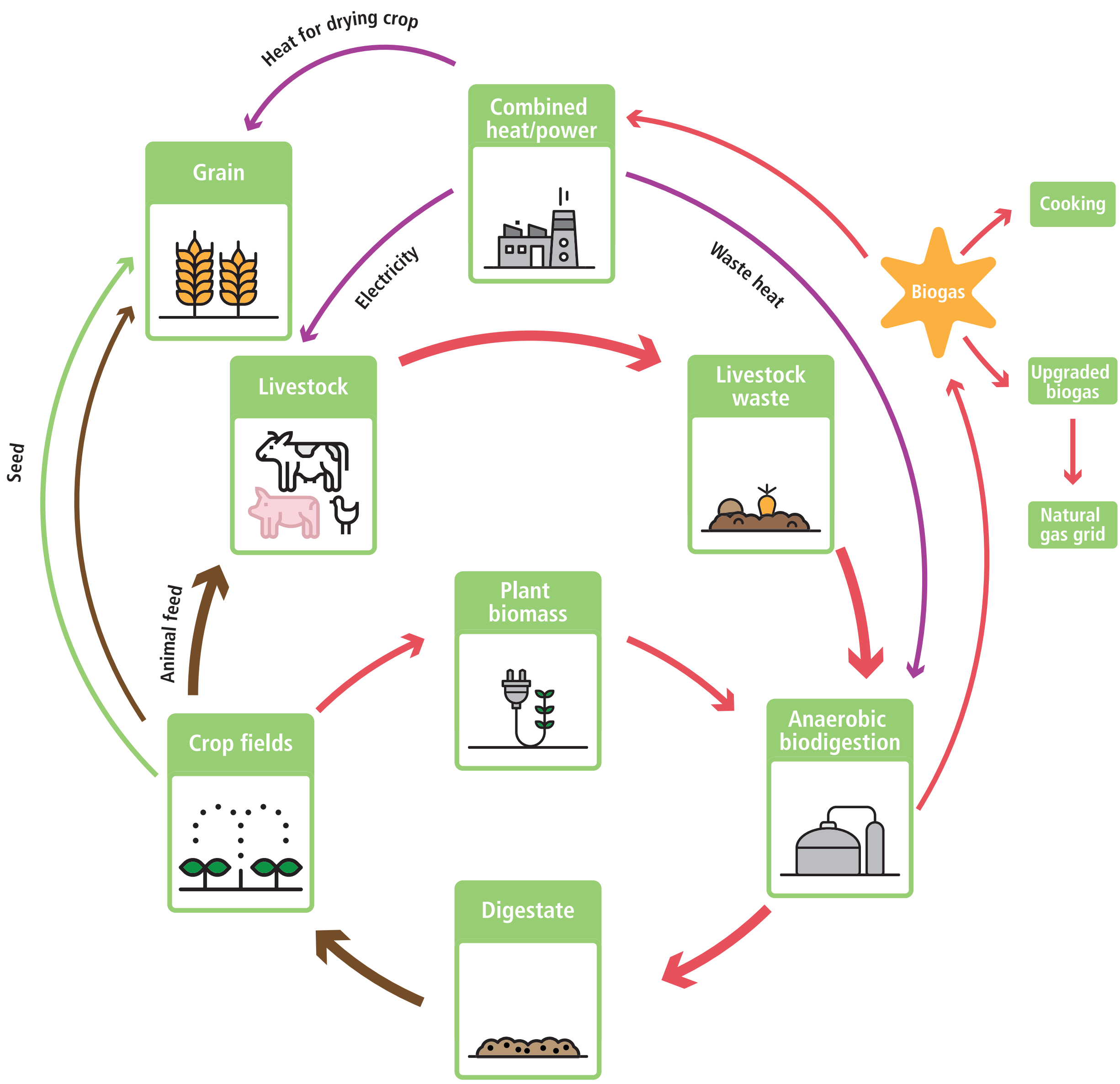
## 3.3.2 Bioenergy technologies

### *3.3.2.1 Anaerobic digestion*

Anaerobic digestion is a series of biological processes in which microorganisms ferment biodegradable material in the absence of oxygen and produce a $CH_4$-rich biogas (Uddin *et al.*, 2021). Biogas can replace natural gas after impurities such as sulphur have been removed. A blend of both manure and crop biomass is often used to optimize $CH_4$ yields through anaerobic co-digestion (AcoD) (Tsapekos *et al.*, 2017). Co-digestion can promote the stabilization of the anaerobic process through complementary effects on microorganisms and nutrient balance, while reducing GHG emissions and processing costs (Kunasta and Xia, 2022). The digestate resulting from anaerobic co-digestion can be used as a biofertilizer or soil amendment as it contains high N and P concentrations (Lamolinara *et al.*, 2022). These complementary effects can contribute to circular bioeconomy processes by producing bioenergy and fertilizer (Figure 14). Biogas from livestock manure and crop biomass can be used to generate electricity, which can be used in livestock production or processing systems.

The combustion of biogas can produce the heat needed to dry crops or reach mesophilic or thermophilic temperatures during AcoD. Under ideal conditions, the AD of organic carbon in wastewaters could generate 380 billion cubic metres of $CH_4$, with a global calorific value of approximately 1 908 billion megajoules (Qadir *et al.*, 2020). Biogas units are widely used at the household level across low- and middle-income countries, where manure often serves as a substrate for biogas production, which in turn replaces firewood for heating and cooking. This substitution helps reduce exposure to harmful particulate pollution (Anderman et al., 2015). To fully realize the environmental benefits of AD, digesters must be gas-tight to prevent $CH_4$ leaks (Baldé *et al.*, 2016). In addition, digestate storage should be integrated into the gas bearing system of the AD plant and low-emission technologies should be used for the land application of digestate (VanderZaag, Glenn and Baldé, 2022). Potential best practices for managing digestate would include fully emptying storage, solid–liquid separation and storage covering. In developing countries, managing the gas production in small rural biogas units can be challenging. Biogas storage during periods when production exceeds demand is essential to avoid the negative climate impact of venting biogas to the atmosphere. Moreover, if the introduction of small-scale biogas production involves shifting from solid to liquid manure management, transporting digestate to areas of the farm where the nutrients can be effectively used for crop production may prove difficult.

FIGURE 14
**Circular bioeconomy in livestock manure and biomass residue management through anaerobic co-digestion**




*Source:* Saha, C.K., Khatun, M.L., Nime, J., Kirtania, K. & Alam, M.M. 2024. Co-digestion-based circular bio-economy to Improve biomethane generation and production of nutrient-enriched digestate in Bangladesh. *Sustainability*, 16(1): 1–18. https://doi.org/10.3390/su16010104

The optimum productivity of the AcoD process depends on the biodegradability of organic matter, the chemical composition of the substrate, and operational parameters such as temperature, pH, the C:N ratio and the organic loading rate (OLR) (Table 14). Anaerobic co-digestion can take place at three temperature regimes: psychrophilic (~25 °C), mesophilic (~35 °C) and thermophilic (~55 °C) – with the mesophilic being most common (Makamure, Mukmba and Makaka, 2021). The mesophilic process is more stable than the thermophilic one because it can accommodate a greater diversity of microorganisms. The pH can significantly impact AcoD systems by affecting the solubility of organic matter. Although microorganisms differ in their optimal pH range for biogas production, most prefer circumneutral pH. To maximize $CH_4$ yields, keeping a digestate pH of 6.3–7.8 is recommended.

Optimizing the ratio of livestock manure to crop biomass is essential for achieving maximum $CH_4$ yields, as these are strongly influenced by the C:N ratio of substrates, with the optimal ratio ranging between 20 and 30 in digesters (Liu *et al.*, 2009). The combination of two or more substrates in AcoD can optimize the C:N ratio and

TABLE 14
**Key parameters for anaerobic co-digestion (AcoD)**

| Parameter | Optimum value |
|---|---|
| Temperature | Mesophilic – 35 ˚C<br>Thermophilic – 50 ˚C to 60 ˚C |
| pH | 6.3–7.8 |
| C:N | 20:30 |
| Total solid concentration | wet AcoD: TS <10%<br>semi-solid-state AcoD: TS = 10–15%<br>solid-state AcoD: TS >15% |
| Organic loading rate | Depends on the volume and substrate of the reactor (≤3 kg VS/m³/day) |
| Retention time | 10 to 30 days |

*Source:* Authors' own elaboration, adapted from Saha, C.K., Nandi, R., Akter, S., Hossain, S., Kabir, K.B., Kirtania, K., Islam, M.T., Guidugli, L., Reza, M.T. & Alam, M.M. 2024. Technical prospects and challenges of anaerobic co-digestion in Bangladesh: A review. *Renewable and Sustainable Energy Reviews,* 197, 114412. https://doi.org/10.1016/j.rser.2024.114412

the nutrient availability needed for methanogens to produce more biogas, while reducing the extent to which end products such as $NH_3$ inhibit microbial growth or function. Another important factor is the OLR, which refers to the amount of raw material loaded into the digester per unit time and per unit volume. A high OLR can increase microbial diversity and reduce the amount of energy required to heat the biodigester, thereby lowering the costs (Nkuna *et al.*, 2022). It is also necessary to allow for a sufficient retention time for microorganisms to convert organic substrates to biogas, which normally takes between 15 and 30 days (Meegoda *et al.*, 2018). Longer retention times improve effluent quality but reduce reaction rates. Less optimal retention times can lead to the accumulation of volatile fatty acids, which inhibit microbial activity and reduce biogas production. In some countries, existing waste management regulations act as barriers to the adoption of new technologies.

#### *3.3.2.2. Thermochemical processes*

Thermochemical processes include combustion, pyrolysis, gasification and hydrothermal liquefaction (Table 15).

Combustion completely oxidizes manure to produce heat and electricity. While it may be perceived as a simple process, the low value of energy products and carbonaceous deposits may hinder its adoption (Khoshnevisan *et al.*, 2021). Thermochemical technologies have been applied to valorize manure for electricity, transportation fuels, heat, fertilizer and biochar production (Figure 15).

Pyrolysis, the thermal decomposition of biomass in an inert atmosphere, can be classified into slow pyrolysis and fast pyrolysis based on differences in heating and feedstock rates, temperature and residence time. Pyrolysis produces bio-oil, a gaseous fuel, and biochar. Fast pyrolysis operates at 450–650 °C and generates a higher fraction of bio-oil, while slow pyrolysis operates at 300–700 °C over a longer duration and generates more biochar. Biochar is rich in slow-release carbon, and some studies have reported that it increases the organic matter and carbon content of soils. Under some conditions, biochar can improve soil fertility and crop productivity (Hussain *et al.*, 2017).

Gasification has a significant potential for processing livestock manure as it achieves a partial oxidation and molecular dissociation at 600–1000 °C, and produces syngas (Watson *et al.*, 2018). The main combustible components of syngas, carbon monoxide and hydrogen, can be used in boilers or gas turbines to generate electricity or heat, or to manufacture hydrocarbon-based chemicals through the Fischer–Tropsch process. The high moisture content (~80 percent) of most manure limits its direct use in pyrolysis and gasification, as considerable energy is required to dry it sufficiently for it to become a suitable input. Furthermore, net energy yields are sometimes limited, and high volumes of ash and/or tar are sometimes generated. Hydrothermal liquefaction avoids the need for drying, as the process can be applied to high moisture manures in a heated, pressurized and oxygen-free reactor (250–400 °C, 10–20 megapascal) with a retention time of 5 to 90 minutes (Watson *et al.*, 2020). Hydrothermal liquefaction can produce a bio-oil with a heating value similar to petroleum crude oil (28–40 megajoules/kg), which can be upcycled for use in renewable diesel blend stocks (Chen *et al.*, 2018). However, considerable energy is still required to operate the oxygen-free reactor.

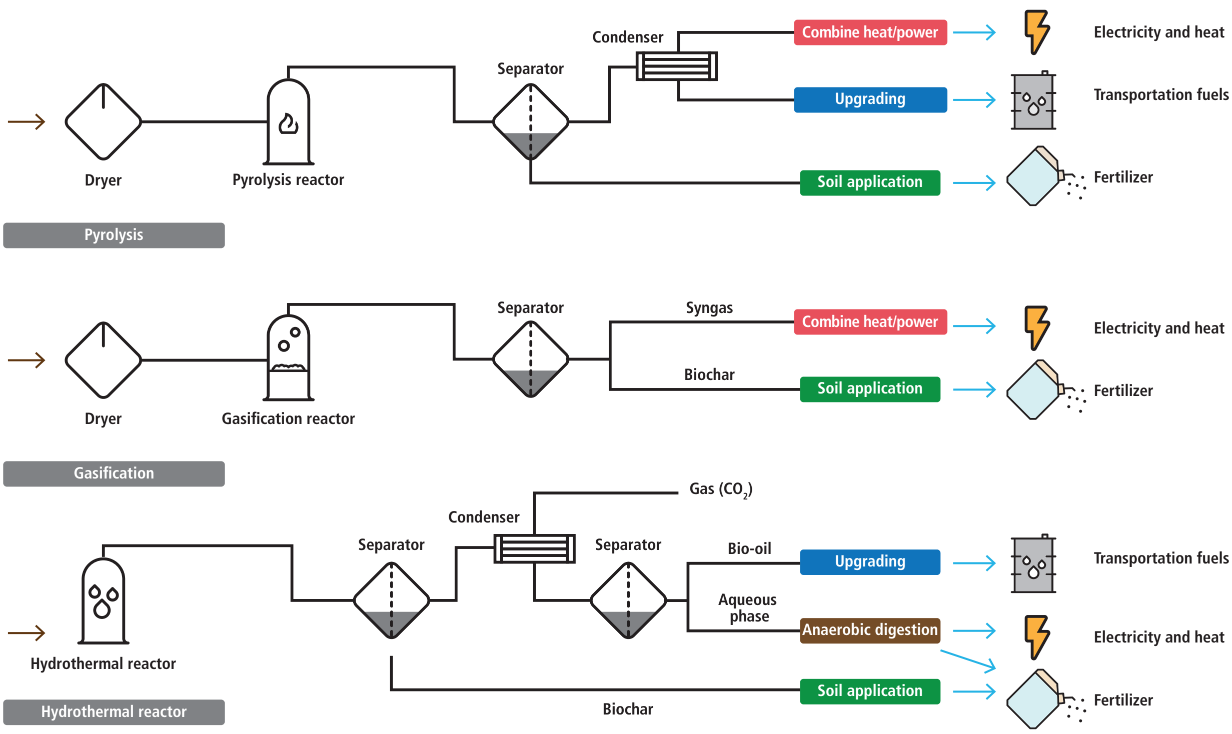
Thermochemical processes can contribute significantly to sustainable energy and biofertilizer production from a circular bioeconomy perspective (Wu *et al.*, 2013; Ou *et al.*, 2022). Additional benefits include the destruction or immobilization of contaminants such as antibiotics, pathogens and/or heavy metals that may be present in manure and other streams (Yang *et al.*, 2022). However, the application of these technologies to manure or other streams is still emerging and requires further research and scaling to be operational at field level. Bio-oil can also have suboptimal properties, such as high oxygen and N concentrations, and issues with viscosity, acidity and poor thermal stability, possibly necessitating additional treatment through hydrotreating and hydrocracking (Lyu, Wu and Zhang, 2015). The consumption of hydrogen, along with high-pressure and high-temperature requirements, increases both operational and capital costs, affecting the technoeconomic feasibility of these technologies. However, there has been increasing interest in applying them to treat municipal sludge and biosolids to destroy organic pollutants (e.g. perfluorooctanoic sulfonate and polyfluoroalkyl substances), while reducing storage and application volumes.

TABLE 15
**Summary of common thermal carbonization technologies**

| Thermal carbonization technologies | Key parameters | Temperature/power range | Residence time | Desired product | Advantages |
|---|---|---|---|---|---|
| Pyrolysis | temperature, heating rate | 300–850 °C | 1–3 h | biochar | simple, robust and cost-effective; applicable to small scale and farm-based biochar production |
| Microwave-assisted pyrolysis | microwave power, microwave irradiation time | 400–500 W | 1–10 min | biochar and biofuel | volumetric, fast, selective and efficient heating |
| Hydrothermal carbonization | temperature, residence time, pressure, water-to-biomass ratio | 120–260 °C | 1–16 h | hydrochar | more suitable to feedstock with high moisture content |
| Gasification | temperature, particle size, residence time, pressure, gasification agent-to-biomass ratio | >800 °C | 10–20 s | syngas | the biochar yield of gasification is less than that of pyrolysis, but biochar contains a high level of alkali salts (e.g. calcium [Ca], potassium [K], silicon [Si], magnesium [Mg]) |

*Source:* Xiang, W., Zhang, X., Chen, J., Zou, W., He, F., Hu, X., Tsang, D.C., Ok, Y.S. & Gao, B. 2020. Biochar technology in wastewater treatment: A critical review. *Chemosphere*, 252, 126539. https://doi.org/10.1016/j.chemosphere.2020.126539

FIGURE 15
**Thermochemical valorization of manure for bioenergy production**




*Source:* Authors' own elaboration, adapted from Bora, R.R., Lei, M., Tester, J.W., Lehmann, J. & You, F. 2020. Life cycle assessment and technoeconomic analysis of thermochemical conversion technologies applied to poultry litter with energy and nutrient recovery. *ACS Sustainable Chemistry & Engineering,* 8(20): 8436–8447. https://doi.org/10.1021/acssuschemeng.0c02860

### 3.3.3 Biofertilizer technologies

Most research and practices in the field of biofertilizer technologies focus on optimizing the supply of macronutrients such as N, P and K to crops, but biofertilizers can also contain at least 11 other essential minerals: Ca, sulphur, Mg, iron, boron, manganese, zinc, copper (Cu), molybdenum, nickel and chlorine (White and Brown, 2010). Nitrogen supply is the main focus of research and agricultural practice as it has the largest and most rapid effect on crop yields and growth, and its benefits are immediately apparent. In contrast, although a sufficient quantity of P during early growth stages is essential for root development and tillering, improvements in crop productivity as a result of P fertilization are often less obvious (Möller *et al.*, 2018). Nutrients present in organic materials take longer to become available for plant uptake than mineral fertilizers, as they must first be mineralized by microbial processes. Often, nutrients are only partly available for plant uptake in the first year of application compared to mineral fertilizers (e.g. 20–70 percent applied N, 10–50 percent applied P). An alternative approach to farm planning may be required to meet crop needs (Jensen, 2013b). Applying organic materials prior to planting may improve conditions, for example by reducing the risk of $NH_3$ toxicity and that of N volatilization. Nutrients such as P and K, as well as micronutrients such as zinc or Cu, are immobile in soils and can accumulate to potentially toxic levels or cause physical issues in soils, such as sodicity, if soil testing is not conducted regularly to inform application rates. Nutrient inputs must also be balanced or supplemented with mineral fertilizers to meet crop nutrient requirement (Jensen, 2013b).

Biofertilizers can improve soil properties, such as pH, water holding capacity, aeration, organic matter content and the nature of beneficial microorganisms in soils (Coonan *et al.*, 2020). Research is increasingly focused on how biofertilizers and management practices can enhance crop production by promoting a balanced nutrient stoichiometry and boosting microbial activity to support the entire soil–plant system (Coonan *et al.*, 2020; Amanullah and Khan, 2023). Nutrient inputs should prioritize the use of organic manure and other recoverable nutrient resources when this is technically and environmentally feasible. Measures that can minimize different forms of N loss from manure applied to land should be implemented, with consideration for local and regional conditions and cost effectiveness. Providing dependable, context-specific N application recommendations, while using generic guidelines, remains a challenge. There is a need for practical tools that would help farmers choose between different nutrients and nutrient sources tailored to specific soil, cropping and climatic conditions, making application more precise and helping to limit N losses. An improved knowledge of crop-specific requirements and soil N mineralization, and the capacity to predict these from remote sensing, will also contribute to making N use more efficient (Sutton *et al.*, 2020). The following should be considered to improve N use and NUE: (a) integrated farm-scale N management planning that accounts for all available N sources; (b) region-specific nutrient management using appropriate N application rates, timing and placement; (c) selection of suitable N sources, such as fertilizers with inhibitors, controlled-release fertilizers, legumes and other biological N fixation methods; (d) adoption of low-emission slurry-spreading technologies; and (e) rapid soil incorporation of $NH_3$-rich organic amendments (Sutton *et al.*, 2020; Amanullah and Khan, 2023).

While manure application constitutes a valuable source of nutrients to soils, its continued use leads to the accumulation of P and the associated risk of pollution in downstream water bodies (Liu *et al.*, 2018). Phosphorus losses tend to increase when the manure contains higher fractions of soluble P, when it is applied to soils with low P sorption capacities or prone to erosion, or when there are limited manure–soil interactions after P application (Kumaragamage and Akinremi, 2018). Factors that can mitigate P loss from manure include reducing P excretion through improved animal diets or additives (i.e. phytases; Dersjant-Li *et al.*, 2015), treating manure to lower the total P or soluble P concentrations through composting or solid–liquid separation (Kumaragamage and Akinremi 2018), or adopting management practices that reduce P accumulation (pre- and post-manure application), such as adding amendments like gypsum (Michalovicz *et al.*, 2017). Adjusting manure application rates to match crop P – rather than N – requirements, and considering the annual timing and weather conditions prior to application, can also address some of these issues (Komiyama, Ito and Saigusa, 2014; Vadas *et al.*, 2017).

Challenges associated with biofertilizer use include lower or heterogenous nutrient concentrations and availability compared to conventional fertilizers. Special equipment is required for spreading bulky materials. Furthermore, biofertilizers usually emit strong odours and may contain pathogens. Lower nutrient-dense materials are often spread before seeding, and higher-nutrient dense materials are top-dressed or fertigated (Voogt *et al.*, 2010). Nutrient imbalances can occur because of losses during or after residual storage, processing or application, often caused by differences in the nutrient-release rate (e.g. water solubility) or applying residuals based on only one nutrient (e.g. N), without using chemical fertilizers to fortify them and achieve balanced nutrient ratios (Zikeli, Deil and Möller, 2017). This can increase the risk of soil alkalinity or salinity, widen the C:N ratios or cause P to accumulate in forms that are hardly available to plants (Mallory and Griffin, 2007; Zikeli, Deil and Möller, 2017). The ongoing testing of biofertilizers and the soils receiving them is essential to prevent nutrient accumulation and to maintain the balance of nutrient inputs over time. Prior to application, the following should be assessed: the properties of the recycled organic material or biofertilizer, including nutrient concentrations, nutrient availability, contaminants such as metals or pathogens; soil characteristics (nutrient status, any soil constraints such as water permeability or surface sealing); the nutrient needs of the selected crop; and any machinery or logistical requirements that must be met to comply with the regulatory guidelines regarding application (e.g. subsurface spreading, distance from water bodies). Potential issues associated with biofertilizer use can be

TABLE 16
**Recommended conditions for efficient composting**

| Parameter | Acceptable range | Optimum range (general) | Optimum range (for reducing greenhouse gas emissions) |
|---|---|---|---|
| C:N ratio | 15–40:1 | 25–30:1 | 22–28:1 |
| Moisture content (%) | 45–65 | 50–60 | 60 |
| Oxygen content (%) | >5 | >5 | |
| pH | 5.5–8.0 | 5.5–8.0 | 6.0 |
| Core temperature (°C) | 40–65 | 55–60 | |
| Particle size diameter (mm) | 5–50 | 5–25 | |

*Source:* Authors' own elaboration, adapted from Lepesteur, M. 2022. Human and livestock pathogens and their control during composting. *Critical Reviews in Environmental Science and Technology*, 52(10): 1639–1683. https://doi.org/10.1080/10643389.2020.1862550 and Liu, Z., Zhu, H., Wang, B. & Zhang, Y. 2009. Effect of ratios of manure to crop on dry anaerobic digestion for biogas production. *Nongye Gongcheng Xuebao/Transactions of the Chinese Society of Agricultural Engineering*, 25(4): 196–200. [Cited 30 June 2025]. http://www.tcsae.org/en/article/id/20090437

addressed through practices such as rotating biofertilizer applications to different fields or paddocks and applying gypsum to combat sodicity.

#### *3.3.3.1 Composting*

Composting is a biological solid waste management tool that aerobically decomposes organic matter to produce compost, heat and $CO_2$ (Lin *et al.*, 2018). Composting methods include windrow piles, reactors, pass-through and static processes (Liu *et al.*, 2023). Widely used under various conditions and relatively inexpensive, composting may require large land areas depending on manure volume and it can generate GHGs or produce leachates if not properly managed (Table 16; Lin *et al.*, 2018). A recent global meta-analysis found that 11 compost parameters (i.e. C:N ratio, pH, salt concentration, electrical conductivity), management practices (N supply) and biophysical conditions (i.e. soil pH and texture, soil organic carbon, crop type, temperature and rainfall) explained 80 percent of the effects of compost on crop yield, soil organic carbon and $N_2O$ emissions (Zhao *et al.*, 2022). Optimizing composting processes could increase crop yields by 40 percent in drier, warmer climates, where soils have an acidic pH and either sandy or clay textures (Zhao *et al.*, 2022). When it comes to reducing GHG emissions during the process, N content in manure was found to have the strongest effect on both emissions and nutrient losses, with windrow-pile composting producing lower GHG emissions compared to other methods such as pass-through composting (Liu *et al.*, 2023). Nitrous oxide was found to be the principal GHG released during composting, while N losses mostly resulted from $NH_3$ emissions (Shan *et al.*, 2021; Liu *et al.*, 2023). Although N losses can be reduced by designing the composting process appropriately, physico-chemical and biological additives such as biochars, nitrification inhibitors, minerals (e.g. zeolite) and microbial inoculants have also been used (Shan *et al.*, 2021). Additives can also improve the fermentation process and promote compost maturation (Shan *et al.*, 2021). Composting has also been shown to mitigate pathogen risk and promote the decomposition of antibiotics in raw livestock manure, with mixed results (i.e. 17–100 percent antibiotic removal rates) depending on composting parameters (Ezzariai *et al.*, 2018). Composting may also increase total P concentrations while reducing water-extractable P, which can lower the downstream water pollution risks associated with manure use (Kumaragamage and Akinremi, 2018).

#### *3.3.3.2 Phosphorus recovery methods*

There are various chemical and biological methods for recovering P from manure. Some bioenergy processes also produce P-rich co-products (e.g. AD for digestate, thermal treatment for ash or biochar), which can be used in agricultural applications. Aqueous-phase methods include ion exchange, precipitation and/or crystallization, and biological technologies such as the biological P removal using microorganisms (e.g. PPB, microalgae), while solid-phase recovery methods include leaching, thermal treatment and adsorption (Jupp *et al.*, 2021). Iron, aluminium, Ca or polymer materials – the most common flocculants used in precipitation methods – can reduce P concentrations to as low as 0.1 mg/L (Perera, Englehardt and Dvorak, 2019). The precipitates can be recovered in the biosolids or further extracted as purified products. However, these processes can increase the volume of sludge produced and the cost of transport, handling and application. While precipitates can effectively reduce soluble P concentrations in the biodigestate's liquid phase, the reduced solubility of P may limit its bioavailability compared to conventional mineral fertilizers. Therefore, there may be a trade-off between efficiently removing P from liquid streams and producing an effective fertilizer. Struvite (i.e. magnesium ammonium phosphate) has been widely investigated for its slow-release fertilizer properties. Other precipitates, such as calcium phosphates, are also being considered. Adding aluminium phosphate to some soil systems can present toxicity issues (e.g. in acidic soils). The solubility of P precipitates can be improved by additional post-processing methods such as wet-chemical extraction with acids or alkali.

However, the addition of chemicals and the need for pH adjustments to maintain a favourable soil pH can limit the cost-effectiveness and the extent to which these products are used instead of chemical fertilizers (Möller *et al.*, 2018).

#### *3.3.3.3 Emerging biofertilizer technologies*

In response to the techno-economic, environmental and social challenges of implementing nutrient recovery technologies in some regions, new technologies are being explored that may be cheaper and easier to implement in isolated regions. These include black soldier fly (BSF), vermicomposting and the production of biochar.

Black soldier fly methods involve the use of *Hermetia illucens* larvae to consume organic residuals, reducing their volume, decreasing the associated odours (Joly and Nikiema, 2019; Smetana, Schmitt and Mathys, 2019) and inactivating pathogens (Gorrens *et al.*, 2021). This process can produce larvae as a feed ingredient, energy source, or outputs such as protein, lipids, chitin and chitosan. Black soldier fly larvae have been used to treat manure from pigs (Hao *et al.*, 2023), cattle, poultry, human sewage (Gold *et al.*, 2020; Nana *et al.*, 2018) and food waste (Gold *et al.*, 2021). The resulting product resembles compost (Gold *et al.*, 2018; Fuhrmann *et al.*, 2022).

Vermicomposting uses earthworms to accelerate the decomposition of organic matter, helping to reduce pathogen levels and control odours (Li, 2011) through synergistic interactions with microorganisms (Kaur, 2020), while also decreasing manure volume by 40–60 percent (Adhikary, 2012). Earthworms have been grown in cattle and pig manure, human sewage, food loss and sludge from the paper and tannery industries (Yadav, Tare and Ahammed, 2012). The vermicast produced, which is rich in N, P, K, micronutrients, humus, beneficial soil microbes including N-fixing bacteria, phosphate solubilizing bacteria, actinomycetes and other growth factors (Kaur, 2020), may be used as an organic fertilizer. Vermiwash is a liquid fertilizer generated by passing water through columns of vermiculture beds to produce a foliar spray (Ansari and Ismail, 2012).

Biochar has been used for wastewater treatment, soil remediation, and gas storage and separation (Xiang *et al.*, 2020). It has been known to improve soil fertility and crop productivity (Yoo *et al.*, 2018), while contributing to soil remediation (Creamer and Gao, 2016). Biochar properties largely depend on the feedstock material, the thermal treatment process parameters and particle size. Some biochar increases soil pH, porosity, and water and nutrient availability (Joseph *et al.*, 2021). Ongoing research is exploring the potential of biochar for soil carbon sequestration (Joseph *et al.*, 2021). Depending on the production method, biochar produced through gasification can precipitate various heavy metals (Xiang *et al.*, 2020). When enriched with ammonium ion, nitrate or phosphate, biochar can function as a form of slow-release organic fertilizer (Zheng *et al.*, 2019). However, if biochar is used to adsorb toxins such as heavy metals or organic pollutants, appropriate measures must be taken to ensure its safe disposal (Muoghalu *et al.*, 2023). Cely *et al.* (2015) reported that the chemical and physical properties of biochar vary according to the manure source (i.e. cattle, chicken and pigs), bedding type (i.e. straw and sawdust) and processing conditions (pyrolysis).

### 3.3.4 Integration of manure and other co-products into the circular bioeconomy

The successful integration of livestock manure and other co-products into the circular bioeconomy for bioenergy and/or biofertilizers production depends on several factors, including the quantity, composition and availability of feedstocks (Hollas *et al.*, 2021; Khoshnevisan *et al.*, 2021; Sefeedpari *et al.*, 2019). Spatial factors such as geographic variability, population density and farm scale further influence how effectively manure can be integrated into farm systems (Scarlat et al., 2018). Additional factors, including supply and demand, animal density and distribution logistics (e.g. volume, form, transportation distances) all influence the ability of key regional industrial and economic organizations to valorize these resources (Flotats *et al.*, 2009; Chojnacka, Moustacas and Mikulewicz, 2022) or to reorganize the livestock value chain, where feasible, to strengthen links between livestock production and biotechnological infrastructure. Adopting such an approach can promote the exchange of resources, increase processing capacity and support the development of new co-products.

The use of biofertilizers can be limited by socioeconomic factors, as farmers may be reluctant to adopt heterogeneous and bulky materials in the absence of clear information as to their nutrient content and potential contaminant concentrations. Their effectiveness can be unpredictable, as it depends on factors such as soil pH, ultraviolet light, storage method and duration. If not properly managed, they could also harbour pathogens that can pose a threat to animal and plant health.

The costs and risks associated with testing new products or changing management practices constitute additional obstacles to adoption (Udemezue and Mmeremikwu, 2021). Capital investments and their returns, along with the lack of international standards and clear guidelines for quality assurance, are perceived as the main barriers to adopting biofertilizers or other bioeconomy practices (Rai *et al.*, 2023). There are numerous examples of farmers collaborating within or across farming sectors as well as with various organizations – whether industrial, governmental or academic – to overcome these barriers (Asai *et al.*, 2018).

Policy and regulatory frameworks, along with new circular business and industrial ecology models, should also be taken into consideration. For example, the EU Circular Economy Action Plan (European Commission, 2012) promotes the use of recycled nutrients as an alternative to those sourced from primary raw materials, in line with its objectives. The key challenge is to ensure that recycled nutrient resources perform as well, or better than, the primary nutrient resources that they replace when it comes to environmental impact. Across the European Union, there are ongoing efforts to develop manure processing technologies that allow manure to be widely used in a safe and agronomically beneficial manner. In many countries, the use of digestate as a biofertilizer is legally restricted because of insufficient information on its quality and safety.

Implementing circular bioeconomy principles to valorize manure and other feedstocks for bioenergy and biofertilizer production requires new business models developed through a collaboration between industrial biowaste plants, farmers and product manufacturers (Chojnacka *et al.*, 2022). Circular bioeconomy business models and concepts, such as bioresource cascades, require collaboration across different industries and stages of the value chain. New standards are needed to harmonize the manufacturing, safety and traceability of biofertilizers. In addition, product stewardship guidelines and practices will help to evaluate the benefits of circular bioeconomy practices, processes and products (Chojnacka *et al.*, 2022).

#### *3.3.4.1. Technology uptake*

The uptake of manure management technologies is complex and influenced by a range of technical, economic, social and structural factors. From a technical standpoint, it is important to conduct trials of technologies directly on farms and clearly demonstrate their ability to consistently solve on-farm problems. Actively involving farmers throughout the research, development and extension process is equally important (Mwangi and Kariuki, 2015). Technology uptake must raise net financial gains by boosting farm productivity and/or profitability, reducing costs associated with waste management regulations, or taking advantage of government incentives (Mwangi and Kariuki, 2015). Technologies must be economically viable over their entire lifetime, spanning construction, operational and labour costs, engineering and maintenance needs, the return on investment period, regulatory and auditing demands, and other types of administrative burden (Hou *et al.*, 2018). Additional factors, such as farm size, can have either positive or negative implications for technology adoption. Larger farms are more likely to adopt new technologies if they can allocate part of their land for trials or if they benefit from economies of scale or vertical integration within the supply chain that can make capital-intensive technologies more profitable (Hou *et al.*, 2018). Smaller farms may be more motivated to adopt technologies that reduce labour costs or raise production levels.

Social factors, such as the farmers' age, can also impact technology adoption. Older farmers tend to exhibit more risk-averse behaviour, whereas younger farmers are generally more open to taking risks and experimenting with new practices and methods. The effect of farmer's gender on technology adoption is not clear-cut. Differences seem to hinge on farmers' ability to access resources such as land, labour and capital, which may be linked to gender. Lower rates of technology adoption by female farmers were reported for manure composting technologies in Burkina Faso and for pig manure recycling in China (Somda *et al.*, 2002; Pan *et al.*, 2021). Gendered sociocultural values and norms can also affect technological uptake, as the household decision maker tends to be male in many cultures and regions. For example, studies have shown that female farmers in Malawi face significant structural disadvantages compared to male plot managers and own only half as much livestock as their male counterparts, resulting in lower adoption rates of manure land-spreading practices (Tufa *et al.*, 2022). Farmer perceptions as to the likely environmental benefits, transportation costs or market demand for biofertilizer products may also affect technology adoption (Tan *et al.*, 2021). In addition, the education level of farmers can increase or stand in the way of technology adoption. Higher levels of education may improve farmers' ability to assess and embrace new technology opportunities (Pan *et al.*, 2021). And yet manure separation technologies were shown to be more commonly adopted by farmers with lower education in the Kingdom of the Netherlands, although these findings may have been determined by other competing factors (e.g. the farmers, despite a lower level of education, were younger and operated larger-sized farms) (Gebrezgabher *et al.*, 2015).

Structural factors can also act as barriers for technology adoption. For example, licensing arrangements can hinder technology uptake if farmers and licensing authorities have a poor understanding of how the technology operates (Hou *et al.*, 2018). A lack of harmonization between government regulations at different levels (e.g. local, state/regional/provincial, national) can also limit technology adoption, as varying technology or waste regulations across jurisdictions may affect farmers or their supply chains (Arsic *et al.*, 2022). Community support, or lack thereof, may also impact licensing approvals for certain technologies (Hou *et al.*, 2018). Lastly, some countries may have inadequate or poorly defined policy and regulatory frameworks, making them difficult to navigate and implement effectively. According to Ndambi *et al*. (2019), smallholder farmers in sub-Saharan Africa find navigating the regulatory environment for manure management difficult. This is down to the absence

BOX 9

**Case study: Recycling nutrients from manure and post-consumer organics in Australia**

With a population of 26.6 million people, Australia produces up to 30 million cattle (of which 1.5 million in feedlots at any one time), 700 million meat chickens and 5.8 million pigs annually (ABARES, 2023). An estimated 1.9 million tonnes of beef feedlot manure, 1.1 million tonnes of spent chicken litter and 1.4 million tonnes of biosolids are produced every year (DAFF, 2007; RIRDC, 2024; Marchuk *et al.*, 2023). The circular bioeconomy presents opportunities for closing nutrient loops in agriculture, as Australia heavily relies on fertilizer imports for its crop production; 4.5 million tonnes of nitrogen fertilizers and 1.7 million tonnes of phosphate fertilizers were imported in 2023 (ABARES, 2023). While local manure and biosolid reuse is relatively high, scaling these practices is challenging for a number of reasons, including limited possibilities of transporting bulky materials across Australia's vast land mass and the absence of centralized biomass data needed to inform larger regional or national investment decisions in bioenergy and biofertilizer production. That said, various local and national innovations designed to support the circular bioeconomy are in the pipeline.

**Local: Granulated beef feedlot manure**

Australia's largest feedlot has a capacity of 800 000 head and can produce around 100 000 tonnes of manure per year. A combination of regulatory, weather and physical application factors has made their bulk manure marketable within 40 km of their feedlot.

Mort & Co produce a range of granulated manure fertilizers. In a bid to expand the market for their manure, the company manufactures tailored products that can be stored and applied, using existing farming equipment.

**National: Mapping biomass resources**

In 2021, the Australian Renewable Energy Agency (ARENA) commissioned a comprehensive national map of biomass resources for bioenergy (Australian Biomass for Bioenergy Assessment [ABBA]). This interactive map of Australia includes livestock residues, cropping, forestry, horticulture and solid organic wastes. The data are being used to identify suitable regions for industrial symbiosis and technology investment. New mapping tools are being developed to support industry and government decision-making.

*Source:* Authors' own elaboration, adapted from Nugent, T. 2021. Australian Biomass for Bioenergy Assessment 2015–2021. Wagga Wagga, Australia, AgriFutures Australia. https://arena.gov.au/assets/2021/04/australian-biomass-for-bioenergy-assessment-final-report.pdf

of specific policies, an incoherent policy environment resulting from multiple ministries sharing the responsibility for manure management, and little effort to enforce legislation or promote best practices.

**Recommendations and findings**

- Actively involving farmers in research, development and engineering activities helps to ensure that technologies are designed and implemented in ways that meet their needs.
- Testing the characteristics of waste or biofertilizers, as well as the soil conditions on the farm where they will be applied, is key to improving nutrient-use efficiency and reducing the risk of contamination.
- Developing evidence-based policies, regulations and incentives or fees for effective manure management or nutrient recycling technologies is a way of giving assurance to farmers who are considering adopting new management practices or technologies.
- Further research is needed to identify the types of farmers who may require additional support for technology uptake across varying scales, sectors, regions and cultural contexts.
- Extension activities, following installation or a change of practice, can boost technology uptake, especially among farmers with limited access to resources.
- A survey of over 700 farmers in China showed that digital-based articles or videos shared via government websites and apps were more effective in helping elderly and smallholder farmers adopt soil fertilization technologies and other innovative farming practices, such as water-saving irrigation and pest management, than younger farmers or those with mid-sized properties (Gao *et al.*, 2020).
- Internet usage has been shown to increase farmers' willingness to convert untreated manure into organic fertilizer by 30–50 percent by making widely available on-demand training resources (Li *et al.*, 2024).

# Chapter 4
# Policy and regulations

## 4.1 POLICIES

Policies covering the use of co-products in livestock production tend to be split into two areas, which then need to be considered together: bioeconomy policies and circular economy policies. Whereas bioeconomy policies focus on the use of biomass, of which only a portion is circular, circular economy policies are concerned with reusing and recycling products, whose components may be other than biomass.

### 4.1.1 Bioeconomy policies

To date, bioeconomy-related policies have been published in more than 60 countries and regions, of which 24 have adopted dedicated bioeconomy policies. These include Australia, Costa Rica, East Africa, the European Union, Faroe Islands, France, Germany, Greenland, Iceland, Ireland, Italy, Japan, Latvia, Malaysia, South Africa, Spain, Sweden, Thailand, the United Kingdom, the United States of America (FAO, 2024a; IACGB, 2020). In most countries, bioeconomy policies cover all locally available biomass. In contrast, some nations have focused their policies on specific biomass sources, such as marine (e.g. Portugal) or forest sources (e.g. Finland, Canada). Furthermore, emerging bioeconomy-related policies in some countries focus on bioenergy and biofuels (e.g. Ghana, Kenya, Nigeria, Mozambique, Senegal and Uganda). In contrast, others concentrate on bioprospecting biomass sources, taking into account traditional bioresources and Indigenous knowledge (e.g. Kenya, Mauritius). In some countries, bioeconomy policies fall under other policy frameworks, such as circular economy, research and development, or rural development policies (Haarich *et al.*, 2022). The recent trend has been for a growing convergence of bioeconomy and the circular economy, with bioeconomy policies increasingly recognizing the potential of residual materials for use as biomass (IACGB, 2020; Stegman, Londo and Junginger, 2020).

Depending on the region or country, various key elements are included in bioeconomy policies. While the sustainable production of biomass, primarily from agriculture and forestry, is often addressed, the production of biomass from livestock tends to be overlooked (Priefer, Jörissen and Frör, 2017; Muscat *et al.*, 2021). A bio-based economy or industry is established through the development of biorefineries and bioresource cascades enabled by eco-industrial symbiosis (Muscat *et al.*, 2021), biotechnology innovation and bioenergy production. Although food production, including ASF, clearly falls within the scope of the bioeconomy, few policies explicitly address it. In the context of policy development and prioritization, livestock production can upcycle biomass (i.e. inedible co-products, food waste) into high value co-products, and it should be given specific consideration in the relevant policy areas (Blair, Moran and Alexander, 2024). Effective policy development can support the contribution of livestock production to circularity. Most bioeconomy policies take a holistic approach, covering many sectors, from biomass production to its various end uses. In contrast, some policies focus on specific facets of the bioeconomy, such as bioenergy, biopharmaceuticals and biotechnology, often as a way of advancing green and blue economy objectives (Priefer, Jörissen and Frör, 2017).

One of the overall aims of bioeconomy policies is to improve the knowledge around the potential use of different biomass resources (McCormick and Kautto, 2013). This includes integrating Indigenous knowledge, promoting research and innovation (e.g. South Africa's IACGB, 2020; DST, 2013) and developing specific value chains, as illustrated by the South African "farmer to pharma" concept (DST, 2013). The use of local biomass (e.g. from livestock production) reduces the dependence on non-renewable resources (Muscat *et al.*, 2021), increases natural resource productivity (e.g. McCormick and Kautto, 2013) and supports regional and rural development (IACGB, 2020). The development of these new uses should, however, properly consider the primary use of biomass, i.e. food (Muscat *et al.*, 2021). Therefore, policies should support the commercialization and adoption of bio-based products (IACGB, 2020), primarily through public procurement and tax policies, but it is equally important to prioritize the use of biomass for food, including ASF.

Bioeconomy policies and approaches have faced criticisms for assuming that biomass production is sustainable, despite possible trade-offs. These may include the reallocation of natural resources – for example, the diversion of dried beet pulp from feed to bioenergy production (Madelrieux *et al.*, 2022) – or adverse impacts on biodiversity, such as the loss of tropical rainforest biodiversity resulting from the intensive cultivation of oil palms for biofuel (Issa, Delbrück and Hamm, 2019). Furthermore, the potential increase of agricultural output for non-food biomass use may impact food affordability and LUC (Issa, Delbrück and Hamm, 2019). To support the development of national bioeconomy policies, FAO (2021) considered bioeconomy policies in their social, economic, environmental and governance dimensions, emphasizing their potential to benefit global communities and the environment. Such policies should adopt a multisectoral approach, fostering interlinkages between sectors while accounting for potential trade-offs and synergies. According to FAO (2021a), bioeconomy policies should promote the sustainable production, use and regeneration of biomass to ensure global food and nutrition security.

### 4.1.2 Circular economy policies

Circular economy policies aim to use resources efficiently and sustainably by reducing waste production and recycling residuals (Reichel *et al.*, 2016). Applied to biomass, this means that biomass residuals such as crop residuals and co-products should be used to produce new biomass sources, thus keeping the biomass in the circular loop, rather than being used for end-of-life products (e.g. biofuels) or destroyed (e.g. burned). However, in some countries, waste management regulations preclude biomass residuals being further used for other purposes by making their destruction mandatory (OECD, 2018).

As the efficient use of resources is key to a circular economy, it is important to assess resource use efficiency from a societal perspective. Technical efficiency, resource productivity and emission intensity are examples of evaluation metrics (Stegmann *et al.*, 2020).

The reduced dependence on natural resources (Stegmann *et al.*, 2020) encourages regional and "place-based solutions". Processes that recycle products, materials and components replace fossil fuel resources with renewables, thereby reducing extraction and the demand for primary natural resources (Reichel *et al.*, 2016; Bezema, 2016). Minimizing waste production and keeping components within circularity loops prevents their loss and removal from the economy and extends their lifetime (Reichel, De Schoenmakere and Gillabel, 2016).

Key enablers for developing a circular economy include ensuring that the materials from products at the end of their life are recyclable, reforming tax policies to discourage pollution and removing incentives for the production of end-of-life products (Reichel, De Schoenmakere and Gillabel, 2016; OECD, 2018). A circular economy relies on collaboration and transparency across the food chain to support the use of material cascades (OECD, 2018; Bezema, 2016), while enabling data monitoring and the development of circularity indicators (Reichel *et al.*, 2016).

Regulations specific to certain sectors aim to implement these policies and introduce additional aspects for consideration. For example, the European Union's Waste Framework Directive establishes a waste hierarchy, based on the potential for prevention, reuse, recycling, recovery and disposal, which dedicates the use of co-products to applications with the highest societal value (Priefer *et al.*, 2017; Muscat *et al.*, 2021; Reichel *et al.*, 2016; Bezema, 2016), while ensuring a healthy supply of food and feed for society (Bezema, 2016).

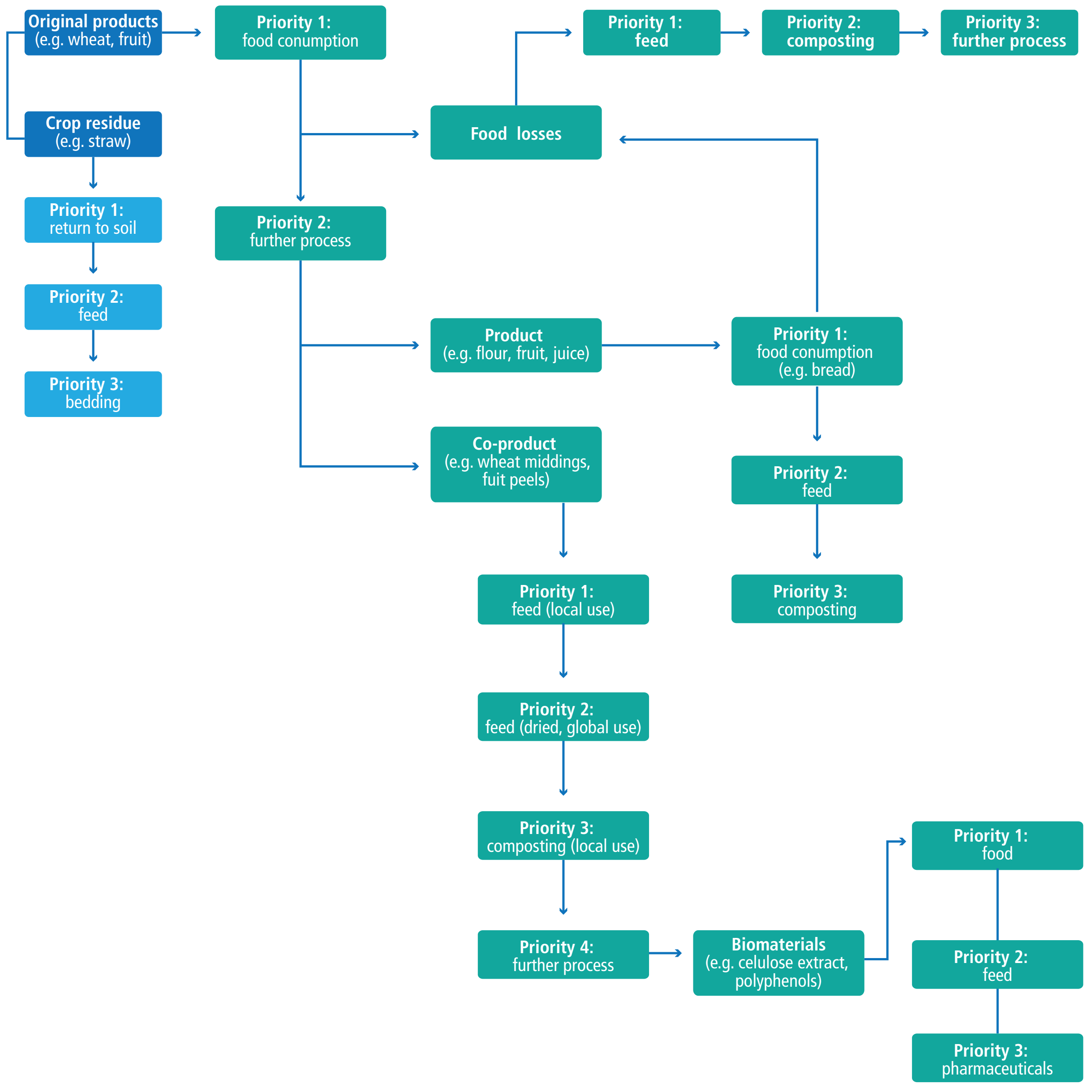
### 4.1.3 Circular bioeconomy systems

The absence of policies tailored to the circular bioeconomy makes it necessary to refer to both circular economy and bioeconomy-related policies in circularity assessments. Contradictions occasionally arise between these two policy areas; for example, the current incentives for bioenergy development can be at odds with the need to develop or produce new materials from biomass in a circular manner (OECD, 2018). The policy goals of a circular bioeconomy often address the most pressing global challenges, such as those associated with climate change, food and energy security (Arsic *et al.*, 2022). Circular bioeconomy policies emphasize that co-products resulting from biomass processing should be kept within the system and not wasted (OECD, 2018; Ramírez, 2013). As a result, in some countries, the definition of waste and regulations preventing it from being reused hinder its transformation into valuable co-products for various sectors (OECD, 2018).

When deciding which of the above-mentioned global challenges should be given priority over the others, trade-offs across sectors must be acknowledged. These trade-offs often stem from competing priorities, such as the conflict between industrial and environmental policies (OECD, 2018). They can also be influenced by market conditions, in which the sectors that pay more for biomass co-products are favoured. To navigate these complexities, clear and effective communication between stakeholders and the public is essential (OECD, 2018; Priefer *et al.*, 2017).

The zero-waste concept leads to the cascading use of biomass (Figure 16; OECD, 2018; Venugopal, 2022; Kleinschmit *et al.*, 2017), involving successive stages of harvesting raw materials, processing them and then further processing the resulting co-products to generate new products. Hence, priority usage and cascading concepts need to be considered to manage biomass efficiently, minimizing conflicts (e.g. use of corn co-product for producing bioenergy rather than feeds for livestock) and maximize synergies (e.g. use of co-products from flour production to feed pigs), while providing food for consumers and generating manure for fertilizer. For this approach to be successfully implemented, an industrial symbiosis needs to be fostered (Reichel *et al.*, 2016) between local sectors and stakeholders engaged in transversal and multidisciplinary activities (Fraga-Corral *et al.*, 2022). Under this scenario, both high- and low-value products are produced according to market demand (Stegmann *et al.*, 2020).

FIGURE 16
**Example of potential cascading use of co-products in an integrated manner**




*Source:* Authors' own elaboration..

## 4.2 FOOD SAFETY

The direct or indirect use (e.g. crop fertilization with digestate, sewage) of co-products in human food and feed must take into account both their nutritional value and the potential health hazards they pose. Antimicrobial resistance, for instance, poses a threat to human and animal health (FAO, 2021b). To counteract it, practices such as the misuse of antimicrobials or their release into the environment must be avoided. Sanitary risks are present throughout the production chain, in the co-product itself as well as during processing, storage and distribution. For co-products to be consumed by animals and humans, they must comply with established food safety regulations and standards.

### 4.2.1 Regulations and standards in place

The regulations and standards aimed at ensuring the safety of humans and livestock vary depending on a country's economic status and consumer demand (Pinotti *et al.*, 2021). Regulations are typically stricter in higher- than in lower-income countries (Van Raamsdonk *et al.*, 2023). The production of co-products that pose high levels of risk may be prohibited in some countries, but not in others (Arujanan and Singaram, 2018; Pinotti *et al.*, 2021; Van Raamsdonk *et al.*, 2023). Concerns about the risk of transmission of bacteria, prions, parasites and viruses have been major barriers to recycling ABPs in feed, with regulations in place restricting this practice in many countries.

The Codex Alimentarius and the International Organization for Standardization (ISO) international standards established for international food trade serve as a benchmark for countries in formulating their national food regulations and standards. These standards are generally not mandatory unless adopted and established as clauses by specific countries. In the European Union, various regulations promote the quality, traceability and safety of feed ingredients during production. Guidelines have been published for the use of food residuals in feed. The European Union has recently reapproved the use of processed animal proteins from poultry, pigs and farmed insects in pig and poultry feeds. However, strict requirements remain in place to prevent cross-contamination and intra-species recycling (see Section 3.2.1). In some countries, standardization, labelling, certification, surveillance and notification systems are in place (Singh, Christensen and Panoutsou, 2021). In others, the lack of appropriate food safety assurance nets for protecting public health remains a major challenge (Teferi, 2020). The FAOLEX database provides a list of the food and nutrition regulations of all countries.

### 4.2.2 Challenges for regulating co-products

Policy interventions and regulations are needed to govern the use of co-products in feed and food, ensuring that their safety requirements are equivalent to those of the conventional products they replace (Leiva *et al.*, 2018; Sandström *et al.*, 2022). Securing regulatory approval for new feed ingredients requires significant resources, including toxicological studies, but standards differ from country to country (Tzachor, Richards and Holt, 2021). Country-specific data are often needed to assess the health risks of new co-products (Javourez, O'Donohue and Hamelin, 2021). However, compared to the main product, fewer studies have explored the impact on human and animal health of co-products (Haque, Fan and Lee, 2023; Socas-Rodríguez *et al.*, 2021), where the risk often depends on climatic conditions (Rao, Bast and De Boer, 2021).

The effective use of a co-product in animal nutrition requires specific analyses to identify potential health risks. However, assessing the food and health quality of co-products is difficult on account of their variable composition (Shurson, 2020). Support from public research organizations and regulatory authorities in improving the safety of co-products can help stakeholders navigate complex and costly approval processes (Lähteenmäki-Uutela *et al.*, 2021). In the context of circular bioeconomy, new ideas, innovative analytical methods and processing technologies should be considered by regulatory authorities, policymakers and legislators when revising or creating policies and regulations (Haque, Fan and Lee, 2023; Rao *et al.*, 2021; Van Raamsdonk *et al.*, 2023) that address risks to humans, livestock or the environment (Boumans *et al.*, 2022).

The rapid adoption of co-products in livestock nutrition also requires that they be compatible with existing distribution processes, channels and infrastructures (Patel *et al.*, 2023; Singh *et al.*, 2021). Where such compatibility is lacking, government incentives or subsidies may be needed to encourage stakeholders to develop the necessary infrastructure (Haque, Fan and Lee, 2023; Shurson, 2020). In the absence of specific regulations, it is recommended that the sectors producing co-products for use in feed follow good hygienic practices, include co-products in their scope and carry out risk analyses related to their use. Moreover, it is recommended that producers of co-products for use in feed implement a hazard analysis and critical control points (HACCP) approach, covering the production of the main product and of all relevant co-products (FAO and IFIF, 2020).

Standards limiting the concentration of hazardous material in feed should be informed by a risk assessment to determine whether higher concentrations of the co-product can be safely included in the diet. These assessments can be guided by the as-low-as-reasonably-achievable (ALARA) principle and must rely on accurate analytical techniques to detect hazards, in addition to toxicological data on the hazards and the livestock species involved. It is also important to consider how toxins are distributed in plants, as some may be present in higher concentrations in the co-product than in the raw material and the processed product. This approach assesses the animal's overall exposure to the hazard, along with the potential impacts of the co-product on animal, human and environmental health.

### 4.2.3 Hazards associated with co-products

In this section, we focus on hazards related to contaminants present in feed ingredients, particularly those that can cause recalls or alerts (i.e. mycotoxins, heavy metals, dioxins and polychlorinated biphenyls [PCBs], pesticide residues, veterinary medicines), and potentially affect livestock, consumers or the environment. A study by FAO and IFIF (2020) exhaustively reviews the hazards related to feed.

**Biological hazards** refer to the presence of microbial pathogens in co-products that can cause diseases in livestock or be transferred to consumers through ASFs, which may lead to zoonosis. *Salmonella* spp., *Campylobacter* spp. and *Escherichia coli* are the most prevalent pathogens found in co-products. Pathogens can enter the system either through the original product or at the post-processing stage, even if the main products are manufactured under hygienic conditions. Given their potential impact, the presence of pathogens in co-products should be managed with the same rigour as in the main product.

**Mycotoxins** are natural secondary metabolites produced mainly by fungi of the genera *Aspergillus*, *Fusarium* and *Penicillium*. Mycotoxins may be produced either as the crop grows in the field (e.g. deoxynivalenol, zearalenone, fumonisin) or during storage (e.g. ochratoxin A, aflatoxin). Field contamination is strongly related to climatic conditions, such as rainfall, temperature and humidity levels. Mycotoxins can be acutely or chronically toxic to humans and livestock, depending on the kind of toxin, the dose and exposure time. Thanks to the detoxifying ability of the rumen microbial population, ruminants are generally less sensitive to most mycotoxins than monogastric livestock, although some toxins have been shown to have deleterious effects to some bovine kidney epithelial cells *in vitro* (Bailey *et al.*, 2019). The mycotoxins with the greatest impact on animal health and growth are aflatoxin B1, ochratoxin A, deoxynivalenol, zearalenone, fumonisin B1 and B2, T2 and HT2 toxin. Some of these mycotoxins, such as aflatoxin B1 and its metabolite M1, as well as ochratoxin A, may also pose a risk to ASF consumers. Ergot is a fungal disease caused by the Clavices genus. A member of this genus, *C. purpurea* produces ergot alkaloids as secondary metabolites (Walkowiak *et al.*, 2022). This fungus is most common in rye and wheat. Given that mycotoxins can also be produced during storage, it is important that post-harvest control strategies be implemented to minimize mycotoxins in the food chain (Magan and Alfred, 2007; Neme and Mohamed, 2017).

**Heavy metals** are minerals that accumulate in the trophic chain and can be toxic to livestock and humans. Regulatory limits are therefore set for feed use. For example, the European Union has limits for cadmium, lead, mercury, arsenic and fluorine. Transfer from feed to ASF tends to be low due to low absorption. However, some heavy metals (e.g. cadmium) have a long half-life and significant levels can accumulate in some food/feed sources (e.g. crustaceans). The National Research Council (NRC, 2005) defined maximum tolerable levels as the dietary level of a mineral that will not impair livestock health or growth when fed for a defined period of time. Maximum tolerance levels are clearly higher than the regulatory limits set for use in feed. The concentration of heavy metals depends on the growing areas, crop fertilization and the manufacturing process of the co-product.

**Dioxins** is a generic term used for polychlorinated dibenzo-p-dioxins and dibenzofurans. Polychlorinated biphenyls (PCBs) are referred to as dioxin-like PCBs (FAO and IFIF, 2020). Dioxins and PCBs are persistent organic pollutants, because of their ubiquity and capacity to bioaccumulate in lipid-rich tissues of livestock. Dioxins are a group of contaminants with common toxicity pathways. Their reproductive, immune and endocrine systems are sensitive targets, especially in developing neonates. The main source of dietary intake for dioxins and PCBs is related to the consumption of ASF. As a result, dioxins and PCBs are a priority hazard for feed and food safety (FAO and IFIF, 2020). Elevated environmental levels have been associated with soil and plants found on flood plains in industrial areas. Depending on the manufacturing process of the main product, dioxins and PCBs may be concentrated in co-product(s), especially when oil or fats such as fish oil and cream from defatted milk are extracted from the main product, as dioxins accumulate in plant oils and adipose tissue. Controls should focus mainly on the evaluation of the manufacturing processes to prevent the entry of dioxins and PCBs into the food chain. For example, lime is used during the drying process of citrus pulp, as a processing aid that impacts the hydrophilic nature of pectin, present in the pulp. The use of lime contaminated by dioxin and PCBs led to the contamination of the dried citrus pulp, making it unsuitable for animal feed (Malisch, 2017). Recycled oils and fats, hydrogenated fats, clay, guar gum and wood shaving are examples of other sources that can potentially be contaminated.

The potential impact of **pesticide** and **veterinary drug** residues associated with the use of feed co-products is low. Organochlorine-based pesticides are problematic, because many remain in the food chain (e.g. dichlorodiphenyltrichloroethane), even if their use has been reduced. The use of co-products in feed may pose certain environmental hazards, mainly linked to the presence of pesticide residues, P, N, zinc and Cu in manure (Hill *et al.*, 2021). Organochlorine pesticides in co-products used in feed should be controlled to avoid further contaminating the environment through manure management. A carry-over of veterinary products can occur in feed mills that produce medicated feed but this issue is not related to the use of co-products. However, antimicrobial use in fermentation to control biological contaminants may lead to their presence in feed co-products.

**Nitrogen** is excreted by livestock as a result of protein digestion and of amino acid and nucleic acid catabolism. Nitrogen excretion depends on N efficiency, which is evaluated by the amount of N retained over the N ingested by the animal (N retained/N ingested ratio). Applying concepts like "ideal protein" or precision feeding, which aim to match protein supply to the animal's specific nutrient requirements, can improve N use efficiency. These concepts are easier to apply when feed ingredients are well characterized. Evaluating the nutritional value of co-products is thus essential to limit N excretion in manure. Moreover, protein digestibility is affected by the co-product's manufacturing process (e.g. heat treatment and Maillard reactions) and by the presence of indigestible fibre.

Phosphorus excretion by livestock is related to the concentration of P in the diet and its digestibility. In monogastric livestock, the levels of P in the diet have been reduced by better aligning intake with nutritional requirements and by supplementing diets with phytases. Phytate limits the biological availability of P in livestock diets. In ruminants, many diets use low levels or even no mineral phosphates, as P levels in ruminant diets are often high and rumen bacteria produce natural phytases. To predict P excretion, it is essential to have a good knowledge of the concentration and form of P in the diet.

The presence of other minerals, such as Cu and zinc, in manure may pose a risk to the environment. And yet both Cu and zinc are systematically added to feed to avoid nutritional deficiencies. When nutritional requirements are exceeded, Cu and zinc concentrations may increase in the manure. Co-products are generally not associated with excess Cu and zinc in livestock diets, although some co-products used in feed – including grape pulp (65 mg Cu/kg), bakery co-products (60 mg Cu/kg) and animal protein meals (120 mg zinc/kg; Blas Beorlegui *et al*., 2021) – may contain higher concentration of these minerals.

## 4.3 PLANETARY BOUNDARIES AND ONE HEALTH FRAMEWORKS FOR HARMONIZING SAFE AND EFFECTIVE BIOCIRCULAR APPROACHES

Circular bioeconomy approaches involve the reuse of residual streams to close resource loops. While circularity can occur in "closed" systems (e.g. on-farm or within single industries), many opportunities exist for transforming co-products into new products for use in other industries. This increased level of biomass movement across geographical areas and across multiple industry interfaces also poses some health and safety risks (WHO, 2018). Among various global health concepts that can provide useful frameworks for monitoring prevention and action on potential health issues, the "One Health" approach stands out as the most cohesive and internationally recognized. It is defined as "an integrated unifying approach that aims to sustainably balance and optimize the health of humans, animals, plants and ecosystems" (FAO, UNEP, WHO & WOAH, 2022, p. 4). Perry *et al.* (2018) suggested that it should be added to the three traditional pillars of economics, society and environment. Potential contaminants must be identified and managed appropriately to prevent harm across human, animal, plant and ecosystem or planetary boundaries.

### 4.3.1 Planetary boundaries and circular bioeconomy approaches

The Planetary Boundaries (PBs) framework is a science-based analysis of human activities that run the risk of destabilizing ecosystems at the planetary scale (Rockström *et al.*, 2023; Steffen *et al.*, 2015). Rooted in the Earth's epochs and biophysical systems, the framework aims to describe a safe operating space for humanity through nine PBs that regulate the planet's stability and resilience (Rockström *et al.*, 2023). They include atmospheric aerosol loading, biogeochemical flows, biosphere integrity, climate change, freshwater use, land-system change, novel entities, ocean acidification, and stratosphere ozone depletion (Steffen *et al.*, 2015). Planetary boundaries are interrelated "core boundaries" (e.g. climate change, biosphere integrity). Six boundaries have now been transgressed beyond their safe operating limit (Richardson *et al.*, 2023). While circular bioeconomy approaches have the potential to support PBs, poorly managed approaches could lead to maladaptive outcomes (Table 17). In relation to the PBs framework, it is equally important to consider how these approaches may impact justice and equity across regions and among vulnerable groups and populations (Rockström *et al.,* 2023).

### 4.3.2 Global animal-human planetary health framework

Three key concepts – One Health, EcoHealth and Planetary Health – offer holistic and overlapping frameworks that support an integrated, systems-based approach to health and risk management within a circular bioeconomy (Amanullah, 2024). The One Health model is the most widely recognized of the three.

While the One Health Global Network promotes an interconnected "whole-of-society" approach, its focus remains on veterinary and medical disciplines. There have been calls to broaden its scope to include aspects more readily emphasized by EcoHealth, such as climate change, biodiversity, agricultural systems, ecology or social science (MacGarr Rabinowitz *et al.*, 2018). This is also listed among the key actions in the current framework of the *One Health Joint Plan of Action (2022–2026): Working together for the health of humans, animals, plants, and the environment* (FAO, UNEP, WHO and WOAH, 2022). This document was developed by FAO, the United Nations Environment Programme (UNEP), the World Health Organization (WHO), and the World Organisation for Animal Health (WOAH). The four UN organizations – known as the Quadripartite – have identified "six action tracks" that jointly support One Health, several of which have direct bearing on circular bioeconomy approaches:

- controlling and eliminating zoonotic, neglected tropical and vector-borne diseases;
- strengthening the assessment, management and communication of food safety risks;
- curbing the silent pandemic of antimicrobial resistance; and
- integrating the environment into One Health.

TABLE 17
**Aligning circular bioeconomy approaches for livestock systems: Sample actions that may support or adversely affect planetary boundaries**

| Planetary boundary | Supportive circular bioeconomy approaches | Maladaptive circular bioeconomy approaches |
|---|---|---|
| Atmospheric aerosol loading | Applying bio-based fertilizers and soil amendments to improve soil structure and water-holding capacity, reducing erosion and likelihood of bushfires | Removing crop stubble or residues to use for bioenergy or biomaterial synthesis, leaving soil exposed and prone to dust generation and erosion |
| Biogeochemical flows | Capturing nutrients from livestock-based organic residuals to return to agricultural lands, decreasing phosphorus (P) and nitrogen (N) applications, thereby reducing nutrient flows to waterways | Poor management of organic residues or biofertilizer applications may lead to excessive nutrient accumulation and discharge to surrounding environments |
| Biosphere integrity | Applying strategic grazing pressure to improve biodiversity outcomes in specific regions (e.g. reduce vegetation to manage weeds or reduce bushfire risk) | Geographic movement of livestock residuals and co-products without considering potential health risks may impact biodiversity (e.g. diseases) |
| Climate change | Developing upcycled feed ingredients to reduce greenhouse gas (GHG) emissions through livestock diets | Poorly managed applications of biofertilizers or manure increase GHG and/or ammonia emissions |
| Freshwater use | Prioritize capture of clean water for reuse in upcycling livestock residuals and co-products (e.g. develop or apply technologies to separate nutrients and clean water from wastewaters) | Failing to consider freshwater requirements when designing circular bioeconomy manufacturing processes or products (e.g. separation technologies) |
| Land-system change | Upcycling co-products into new feed ingredients may reduce the amount of land required to grow crops for use in feed | Changes in land-use disproportionally affect vulnerable groups (e.g. loss of income in developing economies) |

*Source:* Rockström, J., Gupta, J., Qin, D., Lade, S.J., Abrams, J.F., Andersen, L.S., Armstrong McKay, D.I., Bai, X., Bala, G., Bunn, S.E. & Ciobanu, D. 2023. Safe and just Earth system boundaries. *Nature*, 619, 1–10. https://doi.org/10.1038/s41586-023-06083-8

There are currently 22 national action plans for One Health established by countries belonging to the African Union, the Eastern Mediterranean region and the Economic Community of West Africa States (ECOWAS). An additional 91 countries have developed One Health action plans to combat antimicrobial resistance. These action plans should be integrated into circular bioeconomy policies and plans to ensure that approaches are harmonized.

### 4.3.3 Frameworks for identifying health risks posed by circular bioeconomy approaches

#### *4.3.3.1 Circular economy and health framework of the world health organization*

The WHO has developed a framework to "categorize pathways through which the implementation of circular economy models may affect human health and well-being" (WHO, 2018, p. 17). This framework could be applied to circular bioeconomy approaches to identify:

- the category and type of processes and actions needed for biomass consumption and production (e.g. reducing primary resource use, preserving nutrients in the food chain);
- the source of potential impact on or change in risk, whether positive or negative (e.g. linked to the use of co-products);
- the type of health impact that may arise from the circular use of biomass, such as the increased exposure to contaminants;
- the nature of the health impact on humans, animals or the environment, mainly from the maintenance of biomass in the food chain;
- the economic sectors impacted by the potential risk, e.g. the food chain;
- the socioeconomic groups and/or environments affected by specific risks that the use of recycled biomass poses.

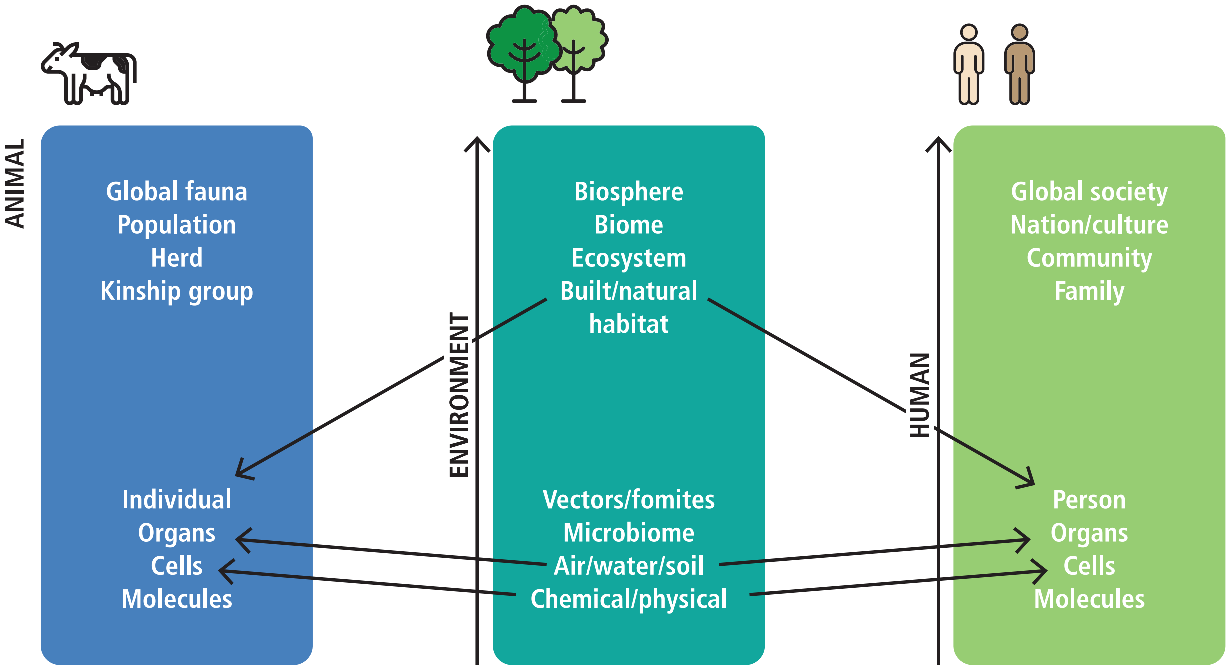
#### *4.3.3.2 One Health systems approach framework: Monitoring sentinel events*

A One Health systems approach can also be used to develop monitoring frameworks for circular bioeconomy approaches. These frameworks help to identify connections within and across animal, human and environmental systems, allowing to identify health risks at the macro level (Figure 17).

### 4.3.4 Policy implications

Several frameworks can be used when developing policies to support a safe and sustainable circular bioeconomy. The policy process consists of five phases (Table 18).

FIGURE 17
**A One Health monitoring framework across animal, human and environmental scales**




*Note:* The arrows indicate where monitoring efforts could link causal effects across and between scales within different systems.
*Source:* MacGarr Rabinowitz, P., Pappaioanou, M., Bardosh, K.L. & Conti, L. 2018. A planetary vision for one health. *BMJ Global Health*, 3(5): e001137. https://doi.org/10.1136/bmjgh-2018-001137

TABLE 18
**Five phases of the policy process and potential roles for FAO Members**

| Policy process phase | Description of issues relevant to this policy process phase in the bioeconomy context | Potential roles for FAO Members |
|---|---|---|
| Agenda setting | Food security, reducing waste streams and lowering the environmental impact of food production are key priorities that call for the development of a policy agenda. A circular bioeconomy offers a promising pathway for achieving those goals in various countries. The importance of livestock production should not be underestimated, especially for exporting countries. | Member Nations can address and prioritize the issues related to the circular use of biomass and consider relevant policies to cover the needs of their communities, including marginalized groups. |
| Design | Indigenous knowledge, research, culture and the economic benefits of circular bioeconomy practices are central elements that can help in designing the relevant policy, aimed at developing circular bioeconomy policies. | Member Nations can assess the potential impacts of alternative policy design options, identify underlying biases and inform multistakeholder deliberation. |
| Adoption | Analysing ecological, economic and social dynamics, as well as understanding the institutional, legal, financial and political context of decision-making, can help foster policy uptake. This requires the involvement of stakeholders across the food chain, ensuring that circular bioeconomy policies reflect the interests of the various groups. | Member Nations can document and raise awareness of how the expected costs and benefits of policy adoption are socially distributed. |
| Implementation | Policy implementation must take into account the resources actually available to support implementation, the skills of the actors involved, as well as the values and interests motivating collective action. | Associations in Member Nations can assist with the institutional capacity assessment needed to implement policies and support the development of capacities between societies. |
| Evaluation and reform | Evaluating the outcomes of circular bioeconomy policies can highlight the need for adjustments and reveal new challenges or trade-offs linked to their implementation. Comparative analysis with other countries can also inform the evaluation process, for example, by shaping the political agenda in a way that translates into budget decisions or market closures. | Engaging in research can help to evaluate policy implementation, including the variety of outcomes across different regions and social groups, providing valuable insights for adapting or reforming policy tools. |

*Source:* Adapted from Resnick, D., Babu, S., Haggblade, S., Hendriks, S. & Mather, D. 2015. *Conceptualizing drivers of policy change in agriculture, nutrition, and food security: The kaleidoscope model.* IFPRI (International Food Policy Research Institute) Discussion Paper, No. 01414; Resnick, D., Haggblade, S., Babu, S., Hendriks, S.L. & Mather, D. 2018. The kaleidoscope model of policy change: Applications to food security policy in Zambia. *World Development*, 109, 101–120. https://reliefweb.int/sites/reliefweb.int/files/resources/ifpridp01414.pdf

## Chapter 5

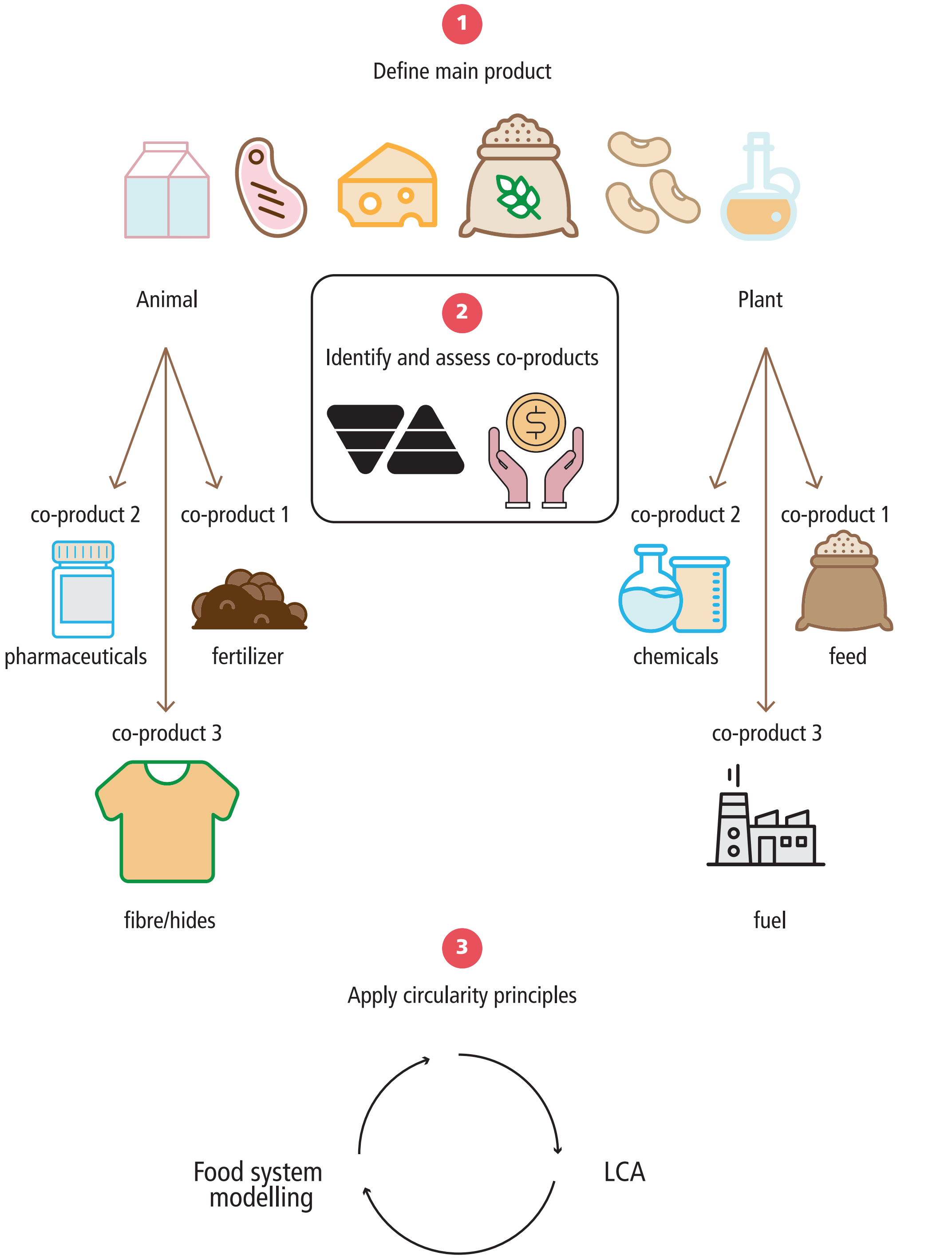
# Assessing circularity in agricultural systems

Agricultural systems produce a range of main products that can be categorized according to producer, processor and end-user. The most common main products derived from livestock are meat, milk and eggs but, in some cases, wool or hides could be considered as the main products. Processing meat, milk and eggs generates co-products. Plants may be consumed directly or further processed – for example extracted for oil or starch, or processed into flour – to provide food. Plant production leads to residuals (e.g. straw, stems) and the process of generating the main product almost invariably gives rise to one or more co-products.

Co-products can be classified as animal- or plant-based. Identifying the co-products that are generated and their optimal use involves a number of steps. Co-products must be assessed based on where they fit within the food-waste hierarchy and value pyramid (Figure 4). The optimal use of co-products is often influenced by nutritional value and policy considerations, such as the safety of co-products and the role that food and environmental safety play in a One Health approach to agricultural sustainability. Many countries have frameworks in place regulating the use of ABPs and PBPs. Plant-based products may be used as feed ingredients for livestock, further fermented to produce fuels such as ethanol, or altered to produce chemicals for other purposes. Livestock production also yields manure that can serve as fertilizer or as a substrate for bioenergy. Finally, livestock products are also used to produce pharmaceuticals, cosmetic products, clothes and shoes (wool and hide).

Once the main product, its co-products and their uses have been defined, metrics are applied to assess the circularity of the agricultural system (i.e. its capacity to effectively retain nutrients). This can involve LCA and food system modelling approaches. Agricultural systems that retain nutrients within the production cycle, as in the case of using PBPs for feed, are considered more circular than those that use PBPs to produce fuel or chemicals, as both are likely to exit the food system. Practices such as landfilling, which fail to retain any nutrients within the food system, result in the lowest circularity. Figure 18 illustrates a schematic approach to the assessment of circular food chains.

FIGURE 18
**Approach to assessing the circularity of co-products that arise from food production in a circular bioeconomy**




*Source:* Authors' own elaboration.

# References


**Abanades, S., Abbaspour, H., Ahmadi, A., Das, B., Ehyaei, M.A., Esmaeilion, F., El Haj Assad, M., Hajilounezhad, T., Jamali, D.H., Hmida, A., Ozgoli, H.A., Safari, S., AlShabi, M. & Bani-Hani, E.H.** 2021. A critical review of biogas production and usage with legislations framework across the globe. *International Journal of Environmental Science and Technology*, 19, 3377–3400. https://doi.org/10.1007/s13762-021-03301-6

**ABARES (Australian Bureau of Agricultural and Resource Economics).** 2024. Rural commodities – meat – general. In: *Agricultural commodity statistics.* [Accessed on 30 June 2025]. https://www.agriculture.gov.au/abares/research-topics/agricultural-outlook/data#_2023

**Abdulla, M.S., Islam, M.S., Kabir, M.E., Dadok, F., Zaber M.A. Al & Sarkar, S.** 2020. Utilization of slaughterhouse by-products: A current scenario in Dhaka city. *Asian Journal of Medical and Biological Research*, 6(4): 809–816. http://dx.doi.org/10.3329/ajmbr.v6i4.51250

**Aboamer, A.A., Khattab, M.S.A., Abo El-Nor, S.A.H., Saleh, H.M., Kholif, A.M., Khattab, I.M., Khorshed, M.M. & Sayed, H.M. El** 2017. A study of nutrient digestibility, milk production and performance of lactating barki ewes fed synchronous least cost ration. *International Journal of Dairy Science*, 12(2): 114–121. https://doi.org/10.3923/ijds.2017.114.121

**ABRA (Associação Brasileira de Reciclagem Animal** [Brazilian Animal Recycling Association]). 2022. *Anuário ABRA setor de reciclagem animal*. https://abra.ind.br/abra/wp-content/uploads/2023/11/20231113-Anuario-ABRA-2022.pdf

**Adesogan, A.T., Arriola, K.G., Jiang, Y., Oyebade, A., Paula, E.M., Pech-Cervantes, A.A., Romero, J.J., Ferraretto, L.F. & Vyas, D.** 2019. Symposium review: Technologies for improving fiber utilization. *Journal of Dairy Science*, 102(6): 5726–5755. https://doi.org/10.3168/jds.2018-15334

**Adhikary, S.** 2012. Vermicompost, the story of organic gold: A review. *Agricultural Sciences*, 3, 905–917. https://doi.org/10.4236/as.2012.37110

**Ahmadi, K. & Amini, B.** 2014. Determination of chemical composition and suitable level of wheat middlings in broiler diets. *International Journal of Plant, Animal and Environmental Sciences*, 4(2): 454–459. https://www.fortunejournals.com/ijpaes/admin/php/uploads/540_pdf.pdf

**Ahmed, M.A., Nematallah, G.M.A., Marwan, A.M.A. & Gihan, M.E.-M.** 2018. Using feed additives for better utilization of phosphorus and nitrogen in broilers feeds. *Journal of Environmental Science*, 44(2): 61–80. http://doi.org/10.21608/jes.2018.35499

**Aina, S., Du Plessis, B., Mjimba, V. & Brink, H.** 2022. Eggshell valorization: Membrane removal, calcium oxide synthesis, and biochemical compound recovery towards cleaner production. *Biointerface Research in Applied Chemistry*, 12(5): 5870–5883. http://dx.doi.org/10.33263/BRIAC125.58705883

**Ajakaiye, J.J., Ayo, J.O. & Ojo, S.A.** 2010. Effects of heat stress on some blood parameters and egg production of Shika Brown layer chickens transported by road. *Biological Research*, 43(2): 183–189. https://doi.org/10.4067/S0716-97602010000200006

**Akay, A. & Sert, D.** 2020. The effects of whey application on the soil biological properties and plant growth. *Eurasian Journal of Soil Science*, 9(4): 349–355. https://doi.org/10.18393/ejss.785380

**Akbar, A. & Ali, I.** 2017. Value-added by-products from sugar processing industries. In: A.K. Anal, ed. *Food processing by-products and their utilization,* pp. 509–534. Hoboken, USA, Wiley. https://doi.org/10.1002/9781118432921.ch21

**Akinyele, B.J., Olaniyi, O.O. & Arotupin, D.J.** 2011. Bioconversion of selected agricultural wastes and associated enzymes by *Volvariella volvacea*: An edible mushroom. *Research Journal of Microbiology,* 6(1): 63-70. http://dx.doi.org/10.3923/jm.2011.63.70

**Allafi, F., Hossain, M.S., Lalung, J., Shaah, M., Salehabadi, A., Ahmad, M.I. & Shadi, A.** 2022. Advancements in applications of natural wool fiber. Review. *Journal of Natural Fibers*, 19(2): 497–512. https://doi.org/10.1080/15440478.2020.1745128

**Amanullah, A. & Khan, U.** 2023. Advancing sustainable agriculture with beneficial microbes: Enhancing crop growth and yield for food security and human health. *Advances in Modern Agriculture,* 4(2). https://doi.org/10.54517/ama.v4i2.2426

**Amanullah, P.** 2024. *Integrated agriculture – An approach for sustainable agriculture*. 387 pp. Berlin, De Gruyter.

**Anderman, T.L., DeFries, R.S., Wood, S.A., Remans, R., Ahuja, R. & Ulla, S.E.** 2015. Biogas cook stoves for healthy and sustainable diets? A case study in Southern India. *Frontiers in Nutrition*, 2, article 28. https://doi.org/10.3389/fnut.2015.00028

**Ansari, A.A. & Ismail, S.A.** 2012. *Earthworms and vermiculture biotechnology*. Earthworms and vermiculture biotechnology. In: S. Kumar & A. Bharti, eds. *Management of organic waste*, pp. 87–96. London, IntechOpen. https://doi.org/10.5772/30957

**Appels, L., Lauwers, J., Degrève, J., Helsen, L., Lievens, B., Willems, K., Van Impe, J. & Dewil, R.** 2011. Anaerobic digestion in global bio-energy production: Potential and research challenges. *Renewable and Sustainable Energy Reviews*, 15(9): 4295–4301. https://doi.org/10.1016/j.rser.2011.07.121

**Aquino, D., Del Barrio, A., Trach, N.X., Hai, N.T., Khang, D.N., Toan, N.T. & Van Hung, N.** 2020. Rice straw-based fodder for ruminants. In: M. Gummert, N.V. Hung, P. Chivenge & B. Douthwaite, eds. *Sustainable Rice Straw Management*, pp. 111–129. Heidelberg, Germany, Springer International Publishing. https://doi.org/10.1007/978-3-030-32373-8_7

**Arsic, M., O'Sullivan, C.A., Wasson, A.P., Juliano, P., MacMillan, C.P., Antille, D.L., Haling, R.E. & Clarke, W.P.** 2022. Australia needs a national policy approach to successfully implement circular bioeconomy in agriculture and food systems. *Farm Policy Journal*, 19(3): 46–60. https://acrobat.adobe.com/link/review?uri=urn:aaid:scds:US:-fa0598de-5e83-4bf9-bd47-cff3fe3ec8d4

**Arujanan, M. & Singaram, M.** 2018. The biotechnology and bioeconomy landscape in Malaysia. *New Biotechnology*, 40, part A, 52–59. https://doi.org/10.1016/j.nbt.2017.06.004

**Asai, M., Moraine, M., Ryschawy, J., De Wit, J., Hoshide, A.K. & Martin, G.** 2018. Critical factors for crop–livestock integration beyond the farm level: A cross-analysis of worldwide case studies. *Land Use Policy*, 73, 184–194. https://doi.org/10.1016/j.landusepol.2017.12.010

**Atta Elmnan, B.A. & Ismeal, R.A.** 2019. *In vitro* digestibility and *in situ* degradability of sugarcane bagasse treated with urea as energy source in total mixed ration for goat. *Online Journal of Animal and Feed Research*, 9(2): 86–91. https://www.researchgate.net/publication/359437356_In_Vitro_DIGESTIBILITY_AND_In_Situ_DEGRADABILITY_OF_SUGARCANE_BAGASSE_TREATED_WITH_UREA_AS_ENERGY_SOURCE_IN_TOTAL_MIXED_RATION_FOR_GOAT

**Badaoui, O., Djebli, A. & Hanini, S.** 2022. Solar drying of apple and orange waste: Evaluation of a new thermodynamic approach, and characterization analysis. *Renewable Energy*, 199, 1593–1605. https://doi.org/10.1016/j.renene.2022.09.098

**Bai, X., Luo, W., Jiang, Y., Zhang, Z., Chen, Z. & Zhou, J.** 2022. Flush of nitrous oxide emissions from plastic greenhouse soil during initial application of poultry manure. *CLEAN – Soil, Air, Water*, 50(2): 2100038. https://doi.org/10.1002/clen.202100038

**Bai, Z., Wang, X., Wu, X., Wang, W., Liu, L., Zhang, X., Fan, X. & Ma, L.** 2021. China requires region-specific manure treatment and recycling technologies. *Circular Agricultural Systems*, 1(1): 1-7. https://doi.org/10.48130/CAS-2021-0001

**Bailey, J.R., Breton, J., Panic, G., Cogan, T.A., Bailey, M., Swann, J.R. & Lee, M.R.F.** 2019. The mycotoxin deoxynivalenol significantly alters the function and metabolism of bovine kidney epithelial cells in vitro. *Toxins*, 11(10): 554. https://doi.org/10.3390/toxins11100554

**Baldé, H., VanderZaag, A.C., Burtt, S., Evans, L., Wagner-Riddle, C., Desjardins, R.L. & MacDonald, J.D.** 2016. Measured versus modeled methane emissions from separated liquid dairy manure show large model underestimates. *Agriculture, Ecosystems & Environment*, 230, 261–270. https://doi.org/10.1016/j.agee.2016.06.016

**Bampidis, V.A. & Robinson, P.H.** 2006. Citrus by-products as ruminant feeds: A review. *Animal Feed Science and Technology*, 128(3–4): 175–217. https://doi.org/10.1016/j.anifeedsci.2005.12.002

**Berlowska, J., Binczarski, M., Dziugan, P., Wilkowska, A., Kregiel, D. & Witońska, I.** 2018. Sugar beet pulp as a source of valuable biotechnological products. In: A.M. Holban & A.M. Grumezescu. eds. *Advances in biotechnology for food industry*, pp. 359–392. Amsterdam, Elsevier. https://doi.org/10.1016/B978-0-12-811443-8.00013-X

**Benjakul, S., Oungbho, K., Visessanguan, W., Thiansilakul, Y. & Roytrakul, S.** 2009. Characteristics of gelatin from the skins of bigeye snapper, *Priacanthus tayenus* and *Priacanthus macracanthus*. *Food Chemistry*, 116(5): 445–451. https://doi.org/10.1016/j.foodchem.2009.02.063

**Berbel, J. & Posadillo, A.** 2018. Review and analysis of alternatives for the valorisation of agro-industrial olive oil by-products. *Sustainability*, 10(1): 237. https://doi.org/10.3390/su10010237

**Bernard, S.** 1995. Some aspects of in vitro regeneration of bread wheat. *Agronomie*, 15(7–8): 499–500. https://doi.org/10.1051/agro:19950729

**Betancor, M.B., Sprague, M., Usher, S., Sayanova, O., Campbell, P.J., Napier, J.A. & Tocher, D.R.** 2015. A nutritionally-enhanced oil from transgenic *Camelina sativa* effectively replaces fish oil as a source of eicosapentaenoic acid for fish. *Scientific Reports*, 5(1): 8104. https://doi.org/10.1038/srep08104

**Beynen, A.C., Van Geene, H.W., Grim, H.V. & Jacobs, P. & Van der Vlerk, T.** 2010. Oral administration of gelatin hydrolysate reduces clinical signs of canine osteoarthritis in a double-blind, placebo-controlled trial. *American Journal of Animal and Veterinary Sciences*, 5(2): 102–106. http://dx.doi.org/10.3844/ajavsp.2010.102.106

**Bezema, A.** 2016. Let us discuss how cascading can help implement the circular economy and the bio-economy strategies. *Waste Management & Research*, 34(7): 593–594. https://doi.org/10.1177/0734242X16657973

**Bhathal, A., Spryszak, M., Louizos, C. & Frankel, G.** 2017. Glucosamine and chondroitin use in canines for osteoarthritis. *Open Veterinary Journal*, 7(1): 36–49. https://doi.org/10.4314/ovj.v7i1.6

**Bhatti, H.N., Hasif, M.A., Qaqim, M. & Ata-ur-Rehman.** 2008. Biodiesel production from waste tallow. *Fuel*, 87(13–14): 2961–2966. https://doi.org/10.1016/j.fuel.2008.04.016

**Bicker, A., Ellen, R. & Parkes, P. eds.** 2003. *Indigenous environmental knowledge and its transformations: Critical anthropological perspectives*. 370 pp. London, Routledge.

**Bikker, P. & Jansman, A.J.M.** 2023. Review: Composition and utilisation of feed by monogastric animals in the context of circular food production systems. *Animal*, 17(3): 100892. https://doi.org/10.1016/J.ANIMAL.2023.100892

**Bionda, A., Lopreiato, V., Crepaldi, P., Chiofalo, V., Fazio, E., Oteri, M., Amato, A. & Liotta, L.** 2022. Diet supplemented with olive cake as a model of circular economy: Metabolic and endocrine responses of beef cattle. *Frontiers in Sustainable Food Systems* 6, 1077363. https://doi.org/10.3389/fsufs.2022.1077363

**Bizzuti, B.E., Pérez-Márquez, S., Van Cleef, F. de Oliveira Scarpino, Ovani, V. Silva, Costa, W. Santos, Lima, P. de Mello Tavares, Louvandini, H. & Abdalla, A.L.** 2023. In vitro degradability and methane production from by-products fed to ruminants. *Agronomy*, 13(4): 1043. https://doi.org/10.3390/agronomy13041043

**Blas Beorlegui, C. de, García Rebollar, P., Gorrochategui, M., Mateos, G.G., Cegarra, E., Méndez, J., Santomá, G., Pérez de Ayala, P., Solà-Oriol, D. & Calsamiglia Blancafort, S.** 2021. *FEDNA tables on the composition and nutritional value of raw material for the production of compound animal feed*. 571 pp. Madrid, FEDNA (Fundación Española para el Desarrollo de Nutrición Animal – Spanish Foundation for the Development of Animal Nutrition).

**Blair, K.J., Moran, D. & Alexander, P.** 2024. Worldviews, values and perspectives towards the future of the livestock sector. *Agriculture and Human Values*, 41(1): 91–108. https://doi.org/10.1007/s10460-023-10469-9

Boskot, S. 2009. *Production of pet food: Inclusion of palatability enhancers in dry extruded dog food*. 84 pp. Saarbrücken, Germany, LAP Lambert Academic Publishing.

**Bothast, R.J. & Schlicher, M.A. 2005.** Biotechnological processes for conversion of corn into ethanol. *Applied Microbiology and Biotechnology*, 67, 19–25. https://doi.org/10.1007/S00253-004-1819-8

**Boumans, I.J.M.M., Schop, M., Bracke, M.B.M., De Boer, I.J.M., Gerrits, W.J.J. & Bokkers, E.A.M.** 2022. Feeding food losses and waste to pigs and poultry: Implications for feed quality and production. *Journal of Cleaner Production*, 378, 134623. https://doi.org/10.1016/j.jclepro.2022.134623

**Bozkurt, M., Alçiçek, A. & Cabuk, M.** 2004. The effect of dietary inclusion of meat and bone meal on the performance of laying hens at old age. *South African Journal of Animal Science*, 34(1): 31–36. http://dx.doi.org/10.4314/sajas.v34i1.3807

**Brandolini, A. & Hidalgo, A.** 2012. Wheat germ: Not only a by-product. *International Journal of Food Science Nutrition*, 63(sup. 1): 71–74. https://doi.org/10.3109/09637486.2011.633898

**Barbosa Brião, V., Vieira Salla, A.C., Miorando, T., Hemkemeier, M. & Cadore Favaretto, D.P.** 2019. Water recovery from dairy rinse water by reverse osmosis: Giving value to water and milk solids. *Resources, Conservation & Recycling*, 140, 313–323. https://doi.org/10.1016/j.resconrec.2018.10.007

**Bora, R.R., Lei, M., Tester, J.W., Lehmann, J. & You, F.** 2020. Life cycle assessment and technoeconomic analysis of thermochemical conversion technologies applied to poultry litter with energy and nutrient recovery. *ACS Sustainable Chemistry & Engineering*, 8(20): 8436–8447. https://doi.org/10.1021/acssuschemeng.0c02860

**Bracco, S., Tani, A., Çalıcıoğlu, Ö., Gomez San Juan, M. & Bogdanski, A.** 2019. Indicators to monitor and evaluate the sustainability of bioeconomy: Overview and a proposed way forward. Rome, FAO. https://openknowledge.fao.org/handle/20.500.14283/ca6048en

**Buchanan, D., Martindale, W., Romeih, E. & Hebishy, E.** 2023. Recent advances in whey processing and valorisation: Technological and environmental perspectives. *International Journal of Dairy Technology*, 76(2): 291–312. https://doi.org/10.1111/1471-0307.12935

**Burg, V., Rolli, C., Schnorf, V., Scharfy, D., Anspach, V. & Bowman, G.** 2023. Agricultural biogas plants as a hub to foster circular economy and bioenergy: An assessment using substance and energy flow analysis. *Resources, Conservation and Recycling*, 190, 106770. https://doi.org/10.1016/j.resconrec.2022.106770

**Cai, L., Koziel, J.A., Zhang, S., Heber, A.J., Cortus, E.L., Parker, D.B., Hoff, S.J., Sun, G., Heathcote, K.Y., Jacobson, L.D., Akdeniz, N., Hetchler, B.P., Bereznicki, S.D., Caraway, E.A. & Limi, T.T.** 2015. Odor and odorous chemical emissions from animal buildings: Part 3. Chemical emissions. *Transactions of the ASABE*, 58(5): 1333–1347. https://doi.org/10.13031/trans.58.11199

**Calicioglu, Ö. & Bogdanski, A.** 2021. Linking the bioeconomy to the 2030 sustainable development agenda: Can SDG indicators be used to monitor progress towards a sustainable bioeconomy? *New Biotechnology*, 61, 40–49. https://doi.org/10.1016/j.nbt.2020.10.010

**Calzada, J. & Sigaudo, D.** 2019. Breve diagnóstico del mercado mundial y local de harina y pellets de soja. In: *Bolsa de Comercio de Rosario*. [Cited 30 June 2025]. https://cdi.mecon.gob.ar/bases/doc/bcr/info_sem/1923.pdf

**Caroli, A.M., Chessa, S., Rignanese, D., Martini, M., Salari, F., Altomonte, I., Casoli, C., Pauselli, M., Alicata, M.L., Bonanno, A., Garro, G., Mauriello, R.C.L., Sartore, S., Rasero, R. & Sacchi, P.** 2011. Aspetti della produzione dei piccoli ruminanti con impatto sulla salute umana. *Scienza e Tecnica Lattiero-Casearia*, 62(1): 5–18. https://iris.unipa.it/retrieve/handle/10447/57197/29588/1%20-%20Caroli.pdf

**Casallas-Ojeda, M., Torres-Guevara, L.E., Caicedo-Concha, D.M. & Gómez, M.F.** 2021. Opportunities for waste to energy in the milk production industry: Perspectives for the circular economy. *Sustainability*, 13(22): 12892. https://doi.org/10.3390/su132212892

**Casas, G., Jaworski, N., Htoo, J. & Stein, H.** 2018. Ileal digestibility of amino acids in selected feed ingredients fed to young growing pigs. *Journal of Animal Science*, 96(6): 2361–2370. https://doi.org/10.1093/jas/sky114

**Cely, P., Gasco, G., Paz-Ferreiro, J. & Méndez, A.** 2015. Agronomic properties of biochars from different manure wastes. *Journal of Analytical and Applied Pyrolysis*, 111, 173–182. https://doi.org/10.1016/j.jaap.2014.11.014

**Chalermthai, B., Giwa, A., Ejbye Schmidt, J.. & Taher, H.** 2021. Life cycle assessment of bioplastic production from whey protein obtained from dairy residues. *Bioresource Technology Reports*, 15, 100695. https://doi.org/10.1016/j.biteb.2021.100695

**Chatzipaschali, A.A. & Stamatis, A.G.** 2012. Biotechnological utilization with a focus on anaerobic treatment of cheese whey: Current status and prospects. *Energies*, 5(9): 3492–3525. https://doi.org/10.3390/en5093492

**Chen, K.-W., Lin, L.-C. & Lee, W.-S.** 2014. Analyzing the carbon footprint of the finished bovine leather: A case study of aniline leather. *Energy Procedia*, 61, 1063–1066. https://doi.org/10.1016/j.egypro.2014.11.1023

**Chen, W., Zhang, Y., Lee, T.H., Wu, Z., Si, B., Lee, C.F., Lin, A. & Sharma, B.K.** 2018. Renewable diesel blendstocks produced by hydrothermal liquefaction of wet biowaste. *Nature Sustainability*, 1, 702–710. https://doi.org/10.1038/s41893-018-0172-3

**Chen, Y.-H., Chen, C.-Y. & Wang, H.-T.** 2022. The effect of forage source and concentrated liquid feedstuff supplementation on improving the synchronization of ruminant dietary energy and nitrogen release in vitro. *Fermentation*, 8(9): 443. https://doi.org/10.3390/fermentation8090443

**Chianese, L., Caira, S., Ferranti, P., Laezza, P., Malorni, A., Muchetti, G., Garro, G. & Addeo, F.** 1997. The oligopeptides of sweet and acid cheese whey. *Lait*, 77(6): 699–715. https://doi.org/10.1051/lait:1997650

**Chiba, L.I.** 2000. Protein supplements. In: J. Lewis & L.L. Southern, eds. *Swine nutrition*, chap. 36. Boca Raton, USA, CRC Press. https://doi.org/10.1201/9781420041842

**Chojnacka, K., Moustacas, K. & Mikulewicz, M.** 2022. Valorisation of agri-food waste to fertilisers is a challenge in implementing the circular economy concept in practice. *Environmental Pollution*, 312, 119906. https://doi.org/10.1016/j.envpol.2022.119906

**Chuang, W.-Y., Lin, L.-J., Shih, H.-D., Shy, Y.-M., Chang, S.-C. & Lee, T.-T.** 2021. The potential utilization of high-fiber agricultural by-products as monogastric animal feed and feed additives: A review. *Animals*, 11(7): 298. https://doi.org/10.3390/ani11072098

**Chukwunonso Ossai, I., Shahul Hamid, F. & Hassan, A.** 2022. Micronised keratinous wastes as co-substrates and source of nutrients and microorganisms for trichoremediation of petroleum hydrocarbon polluted soil. *Biocatalysis and Agricultural Biotechnology*, 43, 102346. https://doi.org/10.1016/j.bcab.2022.102346

**Connolly, A., O'Keeffe, M.B., Nongonierma, A.B., Piggott, C.O. & FitzGerald, R.J.** 2017. Isolation of peptides from a novel brewers spent grain protein isolate with potential to modulate glycaemic response. *International Journal of Food Science and Technology*, 52(1): 146–153. https://doi.org/10.1111/ijfs.13260

**Coonan, E.C., Kirkby, C.A., Kirkegaard, J.A., Amidy, M.R., Strong, C.L. & Richardson, A E.** 2020. Microorganisms and nutrient stoichiometry as mediators of soil organic matter dynamics. *Nutrient Cycling in Agroecosystems*, 117, 273–298. https://link.springer.com/article/10.1007/s10705-020-10076-8

**Coppens, J., Grunert, O., Van Den Hende, S., Vanhoutte, I., Boon, N., Haesaert, G. & De Gelder, L.** 2016. The use of microalgae as a high-value organic slow-release fertilizer results in tomatoes with increased carotenoid and sugar levels. *Journal of Applied Phycology*, 28, 2367–2377. https://dx.doi.org/10.1007/s10811-015-0775-2

**Corona, B., Shen, L., Reike, D., Rosales Carreón, J. & Worrell, E.** 2019. Towards sustainable development through the circular economy – A review and critical assessment on current circularity metrics. *Resources, Conservation and Recycling*, 151, 104498. https://doi.org/10.1016/j.resconrec.2019.104498

**CRA (Corn Refiners Association).** 2006. *Corn wet milled feed products*. 4th ed. Washington, DC, Corn Refiners Association. [Cited 2 July 2025]. https://corn.org/wp-content/uploads/2018/10/Feed2006.pdf

**Crawshaw, R.** 2004. *Co-product feeds: Animal feeds from the food and drinks industries*. 285 pp. Nottingham, UK, Notthingham University Press.

**Creamer, A.E. & Gao, B.** 2016. Carbon-based adsorbents for postcombustion $CO_2$ capture: A critical review. *Environmental Science & Technology*, 50(14): 7276–7289. https://doi.org/10.1021/acs.est.6b00627

**DAFF (Department of Agriculture, Fisheries and Forestry).** 2007. *Making the most of animal by-products – Fact sheet series workbook*. Pretoria, DAFF. https://northernaustraliandairyhub.com.au/wp-content/uploads/2014/11/6701Complete_fact_sheets_workbook100507.pdf

**Dahiya, S., Kumar, A.N., Sravan, J.S., Chatterjee, S., Sarkar, O. & Mohan, S.V.** 2018. Food waste biorefinery: Sustainable strategy for circular bioeconomy. *Bioresource Technology*, 248–A, 2–12. https://doi.org/10.1016/j.biortech.2017.07.176

**Dal Prà, A., Ugolini, F., Negri, M., Bortolu, S., Duce, P., Macci, C., Lombardo, A., Benedetti, M., Brajon, G., Guazzini, L., Casini, S., Spagnul, S. & Camilli, F.** 2024. Wool agro-waste biomass and spruce sawdust: Pellets as an organic soil amendment. *Sustainability*, 16(6): 2228. https://doi.org/10.3390/su16062228

**Darch, T., Dunn, R.M., Guy, A., Hawkins, J.M.B., Ash, M., Frimpong, K.A. & Blackwell, M.S.A.** 2019. Fertilizer produced from abattoir waste can contribute to phosphorus sustainability, and biofortify crops with minerals. *PLoS ONE*, 14(9): e0221647. https://doi.org/10.1371/journal.pone.0221647

**De Boer, I.J. & Van Ittersum, M.K.** 2018. *Circularity in agricultural production*. 72 pp. Wageningen, Kingdom of the Netherlands, Wageningen University & Research. https://www.wur.nl/upload_mm/7/5/5/14119893-7258-45e6-b4d0-e514a8b6316a_Circularity-in-agricultural-production-20122018.pdf

**Dersjant-Li, Y., Awati, A., Schulze, H. & Partridge, G.** 2015. Phytase in non-ruminant animal nutrition: A critical review on phytase activities in the gastrointestinal tract and influencing factors. *Journal of the Science of Food and Agriculture*, 95(5): 878–896. https://doi.org/10.1002/jsfa.6998

**Dijkstra, J., France, J., Ellis, J.L., Strathe, A.B., Kebreab, E. & Bannink, A.** 2013. Production efficiency of ruminants: Feed, nitrogen and methane. In: E Kebreab, ed. *Sustainable Animal Agriculture,* pp. 10–25. Boston, USA, CAB International. http://dx.doi.org/10.1079/9781780640426.0010

**Doppenberg, J. & Van Der Aar, P.** 2007. *Biofuels: Implications for the feed industry*. 118 pp. Wageningen, Kingdom of the Netherlands, Wageningen Academic Publishers.

**Doreau, M. & Ferlay, A.** 2015. Linseed: A valuable feedstuff for ruminants. *Oilseeds & Fats Crops and Lipids*, 22(6): D611. https://doi.org/10.1051/ocl/2015042

**Dosch, P.** 1996. *Optimierung der Verwertung von Güllestickstoff durch Separiertechnik und kulturartspezifische Applikationstechniken*. Bayerisches Staatsministerium für Ernährung, Landwirtschaft und Forsten – Bavarian State Ministry of Food, Agriculture and Forestry. Munich, Germany. PhD dissertation.

**Dou, Z.** 2021. Leveraging livestock to promote a circular food system. *Frontiers of Agricultural Science and Engineering*, 8(1): 188–192. https://doi.org/10.15302/J-FASE-2020370

**Dou, Z., Toth, J.D. & Westendorf, M.L.** 2018. Food waste for livestock feeding: Feasibility, safety, and sustainability implications. *Global Food Security*, 17, 154–161. https://doi.org/10.1016/j.gfs.2017.12.003

**DST (Department of Science and Technology).** 2013. *The bio-economy strategy*. Pretoria, DST. https://www.gov.za/sites/default/files/gcis_document/201409/bioeconomy-strategya.pdf

**Dubis, B., Szatkowski, A. & Jankowski, K.J.** 2022. Sewage sludge, digestate, and mineral fertilizer application affects the yield and energy balance of Amur silvergrass. *Industrial Crops and Products*, 175, 114235. https://doi.org/10.1016/j.indcrop.2021.114235

**Dubois, O. & Gomez San Juan, M.** 2016. *How sustainability is addressed in official bioeconomy strategies at international, national and regional levels: An overview*. 48 pp. Rome, FAO. https://openknowledge.fao.org/items/3518602b-596d-4131-831a-f16220979e4a

**Dumont, E., Poser, M., Peu, P. & Couvert, A.** 2020. Biotrickling filters for the removal of gaseous ammonia emissions from livestock facilities. Theoretical prediction of removal efficiency and experimental validation. *Chemical Engineering Journal*, 402, 126188. https://doi.org/10.1016/j.cej.2020.126188

**EFPRA (European Fat Renderers and Processors Association).** 2022. *Sustainability Charter for a circular bioeconomy*. Brussels, EFPRA.

**EFSA (European Food Safety Authority).** 2024. Scientific opinion of the Scientific Panel on Biological Hazards. Parma, Italy, EFSA. [Accessed on 2 July 2025]. https://www.efsa.europa.eu/en

**EIA (Energy Information Administration).** 2018. *Annual energy outlook 2018*. Washington, DC., EIA. [Cited 2 July 2025]. https://www.eia.gov/pressroom/presentations/capuano_02052018.pdf

**Ekvall, T. & Finnveden, G.** 2001. Allocation in ISO 14041 – A critical review. *Journal of Cleaner Production*, 9(3): 197–208. https://doi.org/10.1016/S0959-6526(00)00052-4

**Ekvall, T. & Weidema, B.P.** 2004. System boundaries and input data in consequential life cycle inventory analysis. *The International Journal of Life Cycle Assessment*, 9, 161–171. https://doi.org/10.1007/BF02994190

**Ellen MacArthur Foundation.** 2013. *Towards the circular economy Vol. 1: Economic and business rationale for an accelerated transition*. Cowes, UK, Ellen MacArthur Foundation. https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf

**Ellen MacArthur Foundation.** n.d. Circular economy introduction. In: *Ellen MacArthur Foundation*. Cowes, UK. [Cited 28 March 2025]. https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview

**Emmerling, C., Krein, A. & Junk, J.** 2020. Meta-analysis of strategies to reduce $NH_3$ emissions from slurries in European agriculture and consequences for greenhouse gas emissions. *Agronomy*, 10(11): 1633. http://dx.doi.org/10.3390/agronomy10111633

**Ericksen, P., Stewart, B., Dixon, J., Barling, D., Loring, P., Anderson, M. & Ingram, J.** 2010. The value of a food system approach. In: J. Ingram, P. Ericksen & D. Liverman, eds. *Food security and global environmental change*, pp. 25–45. London, Earthscan. https://researchprofiles.herts.ac.uk/en/publications/the-value-of-a-food-system-approach

**Erişir, Z., Özçelik, M., Azman, M.A., İflazoğlu Mutlu, S., Ş imşek, Ü.G., Baykalır, Y., Arslan, S., Eroğlu, M., Ozan Kocamüftüoğlu, G. & Çiftçi, M.** 2020. The effects of dietary eggshell with membrane and olive leaf extract supplementation on performance, carcass characteristics and some biochemical parameters on quails exposed to heat stress. *Anka Üniversitesi Veteriner Fakültesi Dergisi*, 67(3): 273–279. https://doi.org/10.33988/auvfd.622127

**Erisman, J.W., Sutton, M., Galloway, J., Klimont, Z. & Winiwarter, W.** 2008. How a century of ammonia synthesis changed the world. *Nature Geoscience*, 1, 636–639. https://doi.org/10.1038/ngeo325

**European Commission.** 2019. Directive 2002/32/EC and updates on undesirable substances in animal feed. In: *EUR-Lex*. Brussels. [Cited 30 June 2025]. http://data.europa.eu/eli/dir/2002/32/2019-11-28

**European Commission.** 2012. *Innovating for sustainable growth: A bioeconomy for Europe*. In: *European Environment Agency*. [Cited 30 June 2025]. https://www.eea.europa.eu/policy-documents/innovating-for-sustainable-growth-a

**European Commission.** 2021. Recommendation on the use of the Environmental Footprint methods: Product Environmental Footprint method (Commission Recommendation [EU] 2021/1961). [Cited 21 July 2025]. https://environment.ec.europa.eu/publications/recommendation-use-environmental-footprint-methods_en

**European Union.** 2023. *Best available techniques (BAT) Reference document for the slaughterhouses, animal by-products and/or edible co-products industries*. In: *EUROPA.EU*. [Cited 11 September 2025]. https://op.europa.eu/en/publication-detail/-/publication/5c1858e7-cc85-11ee-b9d9-01aa75ed71a1/language-en

**European Union–Japan CIC (Centre for Industrial Cooperation).** 2021. *Report: The market for biogas plants in Japan and opportunities for EU companies*. In: *EU Business in Japan*. [Cited 30 June 2025]. https://www.eu-japan.eu/eubusinessinjapan/library/publication/report-market-biogas-plants-japan-and-opportunities-eu-companies

**EUROSTAT.** 2023. *Circular economy: Monitoring framework*. In: *EUROSTAT*. [Cited 30 June 2025]. https://ec.europa.eu/eurostat/web/circular-economy/monitoring-framework

**Ezzariai, A., Hafidi, M., Khadra, A., Aemig, Q., Fels, L.El., Barret, M., Merlina, G., Patureau, D. & Pinelli, E.** 2018. Human and veterinary antibiotics during composting of sludge or manure: Global perspectives on persistence, degradation, and resistance genes. *Journal of Hazardous Materials*, 359, 465–481. https://doi.org/10.1016/j.jhazmat.2018.07.092

**FAO.** 2011. *Global food losses and food waste – Extent, causes and prevention*. Rome. http://www.fao.org/3/i2697e/i2697e.pdf

**FAO.** 2016. *FAOSTAT*: *Global protein consumption indicator*. [Accessed on 30 June 2025]. https://www.fao.org/faostat/en/ https://www.fao.org/faostat/en/#data/FBS. Licence: CC-BY-4.0.

**FAO.** 2018a. *Towards sustainable bioeconomy – Lessons learned from case studies*. Rome. https://openknowledge.fao.org/handle/20.500.14283/CA4352EN

**FAO.** 2018b. *Nutrient flows and associated environmental impacts in livestock supply chains: Guidelines for assessment (Version 1)*. Livestock Environmental Assessment and Performance (LEAP) Partnership. 196 pp. Rome. https://openknowledge.fao.org/handle/20.500.14283/ca1328en Licence: CC BY-NC-SA 3.0 IGO.

**FAO.** 2020. *FishStatJ – Software for Fishery and Aquaculture Statistical Time Series*. In: *FishStatJ*. [Accessed on 30 June 2025]. Available at www.fao.org/fishery/en/statistics/software/fishstatj. Licence: CC-BY-4.0.

**FAO.** 2021a. *Strategic Framework 2022–31*. Rome. https://openknowledge.fao.org/server/api/core/bitstreams/29404c26-c71d-4982-a899-77bdb2937eef/content

**FAO.** 2021b. *The FAO Action Plan on Antimicrobial Resistance 2021–2025*. Rome. https://doi.org/10.4060/cb5545en

**FAO.** 2022. Technical Platform on the Measurement and Reduction of Food Loss and Waste (TPFLW). In: *FAO*. Rome. [Cited 30 June 2025]. https://www.fao.org/platform-food-loss-waste/food-loss/food-loss-measurement/en

**FAO.** 2023a. *Contribution of terrestrial animal source food to healthy diets for improved nutrition and health outcomes – An evidence and policy overview on the state of knowledge and gaps*. Rome. https://doi.org/10.4060/cc3912en

**FAO.** 2023b. *FAOSTAT: Livestock primary production*. [Accessed on 30 June 2025]. https://www.fao.org/faostat/en/#data/QL. Licence: CC BY-NC-SA 3.0 IGO.

**FAO.** 2023c. *Pathways towards lower emissions – A global assessment of the greenhouse gas emissions and mitigation options from livestock agrifood systems*. Rome. https://doi.org/10.4060/cc9029en

**FAO.** 2024a. Sustainable bioeconomy for agrifood systems transformation. In: *FAO*. Rome. [Cited 30 June 2025]. https://www.fao.org/in-action/sustainable-and-circular-bioeconomy/overview/en/

**FAO.** 2024b. *The State of World Fisheries and Aquaculture 2024 – Blue Transformation in action*. Rome. https://doi.org/10.4060/cd0683en

**FAO & IFIF (International Feed Industry Federation).** 2020. *Good practices for the feed sector – Implementing the Codex Alimentarius Code of Practice on Good Animal Feeding*. FAO Animal Production and Health Manual No. 24. Rome. https://doi.org/10.4060/cb1761en

**FAO, UNEP (United Nations Environment Programme), WHO (World Health Organization) & WOAH (World Organisation for Animal Health).** 2022. *One Health Joint Plan of Action (2022–2026). Working together for the health of humans, animals, plants and the environment*. Rome. https://doi.org/10.4060/cc2289en

**Faridi, H. & Arabhosseini, A.** 2018. Application of eggshell wastes as valuable and utilizable products: A review. *Research in Agricultural Engineering*, 64(2): 104–114. https://doi.org/10.17221/6/2017-RAE

**FEEDAP (EFSA Panel on Additives and Products or Substances used in Animal Feed),** 2023. Safety and efficacy of a feed additive consisting of pancreatin from porcine pancreas (Pan-zoot) for dogs (Almapharm GmbH + Co KG). *EFSA Journal,* 21(3): 7879. https://doi.org/10.2903/j.efsa.2023.7879

**Feilberg, A. & Sommer, S.G.** 2013. Ammonia and malodorous gases: Sources and abatement technologies. In: S.G. Sommer, M.L. Christensen, T. Schmidt & L.S. Jensen, eds. *Animal manure recycling: Treatment and management*, pp. 153–175. Hoboken, USA, Wiley. https://doi.org/10.1002/9781118676677.ch9

**Ferreira, I.M.P.L.V.O., Pinho, O., Vieira, E. & Tavarela, J.G.** 2010. Brewer's *Saccharomyces* yeast biomass: Characteristics and potential applications. *Trends in Food Science and Technology*, 21(2): 77–84. https://doi.org/10.1016/j.tifs.2009.10.008

**Fitzgerald, A.J., Rai, P.S., Marchbank, T., Taylor, G.W., Ghosh, S., Ritz, B.W. & Playford, R.J.** 2005. Reparative properties of a commercial fish protein hydrolysate preparation. *Gut*, 54(6): 775-781. https://doi.org/10.1136/gut.2004.060608

**Flotats, X., Bonmati, A., Fernández, B. & Magri, A.** 2009. Manure treatment technologies: On-farm versus centralized strategies. NE Spain as case study. *Bioresource Technology*, 100(22): 5519–5526. https://doi.org/10.1016/j.biortech.2008.12.050

**Fraga-Corral, M., Ronza, P., Garcia-Oliveira, P., Pereira, A.G., Losada, A.P., Prieto, M.A., Quiroga, M.I. & Simal-Gandara, J.** 2022. Aquaculture as a circular bio-economy model with Galicia as a study case: How to transform waste into revalorized by-products. *Trends in Food Science and Technology*, 119, 23–35. https://doi.org/10.1016/j.tifs.2021.11.026

**Fuhrmann, A., Wilde, B., Conz, R.F., Kantengwa, S., Konlambigue, M., Masengesho, B., Kintche, K., Kassa, K., Musazura, W., Späth, L. & Gold, M.** 2022. Residues from black soldier fly (*Hermetia illucens*) larvae rearing influence the plant-associated soil microbiome in the short term. *Frontiers in Microbiology*, 13, 994091. https://doi.org/10.3389/fmicb.2022.994091

**Gao, Y., Zhao, D., Yu, L. & Yang, H.** 2020. Influence of a new agricultural technology extension mode on farmers' technology adoption behavior in China. *Journal of Rural Studies*, 76, 173–183. https://doi.org/10.1016/j.jrurstud.2020.04.016

**Garcia, E.P., Mehta, S., Blair, L.A.C., Wells, D.G., Shang, J., Fukushima, T., Fallon, J.R., Garner, C.C. & Marshall, J.** 1998. SAP90 binds and clusters kainate receptors causing incomplete desensitization. *Neuron*, 21(4): 727–739. https://doi.org/10.1016/S0896-6273(00)80590-5

**García, M.C., Marina, M.L., Laborda, F. & Torre, M.** 1998. Chemical characterization of commercial soybean products. *Food Chemistry*, 62(3): 325–331. https://doi.org/10.1016/S0308-8146(97)00231-8

**Gatto, A., Kuiper, M., Van Middelaar, C. & Van Meijl, H. 2024.** Unveiling the economic and environmental impact of policies to promote animal feed for a circular food system. *Resources, Conservation and Recycling*, 200, 107317. https://doi.org/10.1016/j.resconrec.2023.107317

**Gebrezgabher, S.A., Meuwissen, M.P.M., Kruseman, G., Lakner, D. & Oude Lansink, A.G.J.M.** 2015. Factors influencing adoption of manure separation technology in the Netherlands. *Journal of Environmental Management*, 150, 1–8. https://doi.org/10.1016/j.jenvman.2014.10.029

**Gerber, P.J., Uwizeye, A. & Schulte, R.** 2014. Nutrient use efficiency: A valuable approach to benchmark the sustainability of nutrient use in global livestock production? *Current Opinion in Environmental Sustainability*, 9–10, 122–130. https://doi.org/10.1016/j.cosust.2014.09.007

**Ghisellini, P., Cialani, C. & Ulgiati, S.** 2014. A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, 114, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007

**Giacometti, C., Mazzon, M., Cavani, L., Triberti, L., Baldoni, G., Ciavatta, C. & Marzadori, C.** 2021. Rotation and fertilization effects on soil quality and yields in a long term field experiment. *Agronomy*, 11(4): 636. https://doi.org/10.3390/agronomy11040636

**Gilhespy, S.L., Webb, J., Chadwick, D.R., Misselbrook, T.H., Kay, R., Camp, V., Retter, A.L. & Bason, A.** 2009. Will additional straw bedding in buildings housing cattle and pigs reduce ammonia emissions? *Biosystems Engineering*, 102(2): 180–189. http://dx.doi.org/10.1016/j.biosystemseng.2008.10.005

**Giteru, S.G., Ramsey, D.H., Hou, Y., Cong, L., Mohan, A. & Aea, B.** 2022. Wool keratin as a novel alternative protein: A comprehensive review of extraction, purification, nutrition, safety, and food applications. *Comprehensive Reviews in Food Science and Food Safety*, 22(1): 643–687. https://doi.org/10.1111/1541-4337.13087

**Gold, M., Cassar, C.M., Zurbrügg, C., Kreuzer, M., Boulos, S., Diener, S. & Mathys, A.** 2020. Biowaste treatment with black soldier fly larvae: Increasing performance through the formulation of biowastes based on protein and carbohydrates. *Waste Management*, 102, 319–329. https://doi.org/10.1016/j.wasman.2019.10.036

**Gold, M., Ireri, D., Zurbrügg, C., Fowles, T. & Mathys, A.** 2021. Efficient and safe substrates for black soldier fly biowaste treatment along circular economy principles. *Detritus*, 16, 31–40. http://dx.doi.org/10.31025/2611-4135/2021.15116

**Gold, M., Tomberlin, J.K., Diener, S., Zurbrügg, C. & Mathys, A.** 2018. Decomposition of biowaste macronutrients, microbes, and chemicals in black soldier fly larval treatment: A review. *Waste Management*, 82, 302–318. https://doi.org/10.1016/j.wasman.2018.10.022

**Gomez San Juan, M., Harnett, S. & Albinelli, I.** 2022. *Sustainable and circular bioeconomy in the climate agenda: Opportunities to transform agrifood systems*. Rome, FAO. https://doi.org/10.4060/cc2668en

**Gorrens, E., Van Looveren, N., Van Moll, L., Vandeweyer, D., Lachi, D., De Smet, J. & Van Campenhout, L.** 2021. *Staphylococcus aureus* in substrates for black soldier fly larvae (*Hermetia illucens*) and its dynamics during rearing. *Microbiology Spectrum*, 9(3): e02183-21. https://doi.org/10.1128/spectrum.02183-21

**Gottlob, R.O., Hastad, C.W., Lawrence, K.R., Groesbeck, C.N., Goodband, R.D., Tokach, M.D., DeRouchey, J.M., Nelssen, J.L. & Dritz, S.S.** 2004. Effects of increasing meat and bone meal on finishing-pig growth performance. *Kansas Agricultural Experiment Station Research Reports*, 10, 126–131. https://doi.org/10.4148/2378-5977.6918

**Greenwood, P.L.** 2021. An overview of beef production from pasture and feedlot globally, as demand for beef and the need for sustainable practices increase. *Animal*, 15(1): 100295. https://doi.org/10.1016/j.animal.2021.100295

**Grundy, S.M. 2013.** Hypercholesterolemia and metabolic syndrome: Mischievous partners. *Circulation*, 128(suppl. 22): A603. https://doi.org/10.1161/circ.128.suppl_22.A603

**Gudoshnikov, S., Jolly, L. & Spence, D.** 2004. Sugar production. In: *The World Sugar Market*, pp. 133–150. Amsterdam, Elsevier. https://doi.org/10.1016/b978-1-85573-472-2.50015-6

**Gumul, D., Korus, J., Surma, M. & Ziobro, R.** 2020. Pulp obtained after isolation of starch from red and purple potatoes (*Solanum tuberosum* L.) as an innovative ingredient in the production of gluten-free bread. *PLoS ONE*, 15(9): e0229841. https://doi.org/10.1371/journal.pone.0229841

**Gündem, A., & Tarhan, Ö.** 2020. Extraction of collagen and gelatine from animal wastes. *Bulletin of Biotechnology*, 1(1): 1–4. https://dergipark.org.tr/tr/download/article-file/1159668

**Haarich, S. & Kirchmayr-Novak, S., Borzacchiello, M.T., Sanchez Lopez, J. & Avraamides, M.** 2022. Bioeconomy strategy development in EU regions. In: M.T. Borzacchiello, J. Sanchez Lopez & M. Avraamides, eds. *Towards a sustainable bioeconomy monitoring system: Insights for the EU and its Member States*. Luxembourg, Publications Office of the European Union. https://data.europa.eu/doi/10.2760/065902

**Hannon, K. & Trenkle, A.** 1990. Evaluation of condensed molasses fermentation solubles as a nonprotein nitrogen source for ruminants. *Journal of Animal Science*, 68(9): 2634–2641. https://doi.org/10.2527/1990.6892634x

**Hao, J., Liu, S., Luo, A., Zhao, J., Shi, S., Zhang, Y., & Li, C.** 2023. Assessing nursery-finishing pig manures on growth of black soldier fly larvae. *Animals*, 13(3): 452. https://doi.org/10.3390/ani13030452

**Haque, F., Fan, C. & Lee, Y.-Y.** 2023. From waste to value: Addressing the relevance of waste recovery to agricultural sector in line with circular economy. *Journal of Cleaner Production*, 415, 137873. https://doi.org/10.1016/j.jclepro.2023.137873

**Harveson, R.M.** 2013. *History of sugarbeets: An abbreviated history.* Lincoln, USA, University of Nebraska Press. https://extensionpubs.unl.edu/publication/g2076/2011/pdf/view/g2076-2011.pdf

**Hashem, M.A. & Nur-A-Tomal, M.S.** 2018. Tannery solid waste valorization through composite fabrication: A waste-to-wealth approach. *Environmental Progress & Sustainable Energy*, 37(5): 1722–1726. http://dx.doi.org/10.1002/ep.12860

**Haverkort, A.J., Linnemann, A.R., Struik, P.C. & Wiskerke, J.S.C.** 2023. On processing potato. *Potato Research*, 66, 301–338. https://doi.org/10.1007/s11540-022-09562-z

**Hendriks, W.H., Butts, C.A., Thomas, D.V., James, K.A., Morel, P.C. & Verstegen, M.W.** 2002. Nutritional quality and variation of meat and bone meal. *Asian-Australian Journal of Animal Science*, 15(10): 1507–1516. https://www.animbiosci.org/upload/pdf/15_239.pdf

**Heuzé, V. & Tran, G.** 2015a. Rice straw. In: *Feedipedia – Animal Feed Resources Information System.* Paris, INRAE–CIRAD–AFZ–FAO. [Cited 30 June 2025]. https://www.feedipedia.org/node/557

**Heuzé, V., Tran, G., Gomez Cabrera, A. & Lebas, F.** 2015b. Olive oil cake and by-products. In: *Feedipedia – Animal Feed Resources Information System*. Paris, INRAE–CIRAD–AFZ–FAO. [Cited 30 June 2025]. https://www.feedipedia.org/node/32

**Heuzé, V., Tran, G., Baumont, R., Noblet, J., Renaudeau, D., Lessire, M. & Lebas, F.** 2015c. Wheat bran. In: *Feedipedia – Animal Feed Resources Information System.* Paris, INRAE–CIRAD–AFZ–FAO. [Cited 30 June 2025]. https://www.feedipedia.org/node/726

**Heuzé, V., Tran, G. & Lebas, F.** 2015d. Maize germ meal and maize germ. In: *Feedipedia – Animal Feed Resources Information System*. Paris, INRAE–CIRAD–AFZ–FAO. [Cited 30 June 2025]. https://www.feedipedia.org/node/716

**Heuzé, V., Tran, G., Bastianelli, D. & Lebas, F.** 2015e. Rice bran and other rice by-products. In: *Feedipedia – Animal Feed Resources Information System.* Paris, INRAE–CIRAD–AFZ–FAO. [Cited 30 June 2025]. https://www.feedipedia.org/node/750

**Heuzé, V., Tran, G., Chapoutot, P., Noblet, J., Renaudeau, D., Lessire, M. & Lebas, F.** 2015f. Poultry by-product meal. In: *Feedipedia – Animal Feed Resources Information System.* Paris, INRAE–CIRAD–AFZ–FAO. [Cited 30 June 2025]. https://www.feedipedia.org/node/214

**Heuzé, V. & Tran, G.** 2016a. Blood meal. In: *Feedipedia – Animal Feed Resources Information System*. Paris, INRAE–CIRAD–AFZ–FAO. [Cited 30 June 2025]. https://www.feedipedia.org/node/221

**Heuzé, V., Tran, G., Sauvant, D., Noblet, J., Renaudeau, D., Bastianelli, D. & Lebas, F.** 2016b. Palm kernel meal. In: *Feedipedia – Animal Feed Resources Information System*. Paris, INRAE–CIRAD–AFZ–FAO. [Cited 30 June 2025]. https://agritrop.cirad.fr/582554/

**Heuzé, V., Tran, G., Hassoun, P., Bastianelli, D. & Lebas, F.** 2019. Cottonseed meal. In: *Feedipedia – Animal Feed Resources Information System*. Paris, INRAE–CIRAD–AFZ–FAO. [Cited 30 June 2025]. https://www.feedipedia.org/node/550

**Hill, D., Morra, M.J., Stalder, T., Jechalque, S., Top, E., Polland, A.T. & Popova, I.** 2021. Dairy manure as a potential source of crop nutrients and environmental contaminants. *Journal of Environmental Sciences.*, 100, 117–130. https://doi.org/10.1016/j.jes.2020.07.016

**Hira, A., Pacini, H., Attafuah-Wadee, K., Sikander, M., Oruko, R. & Dinan, A.** 2022. Mitigating tannery pollution in sub-Saharan Africa and South Asia. *Journal of Developing Societies*, 38(3): 360–383. https://doi.org/10.1177/0169796X221104856

**Hobson, R. & James, L.** 2015. The addition of whey protein to a carbohydrate–electrolyte drink does not influence post-exercise rehydration. *Journal of Sports Sciences*, 33(1): 77–84. https://doi.org/10.1080/02640414.2014.925570

**Hoffman, L. & Baker, A.** 2011. Market issues and prospects for US distillers' grains supply, use, and price relationships. In: *USDA Economic Research Service*. Washington, DC.. [Cited 30 June 2025]. https://www.ers.usda.gov/publications/pub-details/?pubid=36470 https://www.ers.usda.gov/mediaImport/107533/fds10k01_1_.pdf

**Hollas, C.E., Bolsan, A.C., Venturin, B., Bonassa, G., Tápparo, D.C., Cândido, D., Goldschmidt Antes, F., Vanotti, M.B., Szögi, A.A. & Kunz, A.** 2021. Second-generation phosphorus: Recovery from wastes towards the sustainability of production chains. *Sustainability*, 13(11): 5919. https://doi.org/10.3390/su13115919

**Hou, Y., Velthof, G.L., Case, S.D.C., Oelofse, M., Grignani, C., Balsari, P., Zavattaro, L., Gioelli, F., Bernal, M.P., Fangueiro, D., Trindade, H., Jensen, L.S. & Oenema, O.** 2018. Stakeholder perceptions of manure treatment technologies in Denmark, Italy, the Netherlands and Spain. *Journal of Cleaner Production*, 172, 1620–1630. https://doi.org/10.1016/j.jclepro.2016.10.162

**Huige, N.J.** 2020. Brewery by-products and effluents. In: G.G. Stewart & F.G. Priest, eds. *Handbook of brewing*, pp. 670–729. Boca Raton, USA, CRC Press. https://doi.org/10.1201/9781420015171-22

**Hülsen, T., Batstone, D.J. & Keller, J.** 2014. Phototrophic bacteria for nutrient recovery from domestic wastewater. *Water Research*, 50, 18–26. https://doi.org/10.1016/j.watres.2013.10.051

**Hussain, M., Farooq, M., Nawaz, A., Sadi, A.M.Al, Solaiman, Z.M., Alghamdi, S.S., Ammara, U., Ok, Y.S. & Siddique, K.H.M.** 2017. Biochar for crop production: Potential benefits and risks. *Journal of Soils and Sediments*, 17, 685–716. https://doi.org/10.1007/s11368-016-1360-2

**Hussain, M., Qayum, A., Xiuxiu, Z., Liu, L., Hussain, K., Yue, P., Yue, S., Koko, M.Y.F. & Li, X.** 2021. Potato protein: An emerging source of high quality and allergy free protein, and its possible future based products. *Food Research International*, 148, 110583. https://doi.org/10.1016/j.foodres.2021.110583

**IACGB (International Advisory Council on Global Bioeconomy) and GBS (Global Bioeconomy Summit).** 2020. *Expanding the sustainable bioeconomy – Vision and way forward. Communiqué of the Global Bioeconomy Summit*. In: *GBS2020*. Berlin, Secretariat of the Global Bioeconomy Summit. [Cited 30 June 2025]. https://gbs2020.net/wp-content/uploads/2020/11/GBS2020_IACGB-Communique.pdf

**IBEF (Indian Brand Equity Foundation).** 2023. Leather industry and exports. [Cited 30 June 2025]. https://www.ibef.org/exports/leather-industry-india

**INRAE (Institut national de la recherche agronomique – French National Research Institute for Agriculture, Food and Environment), CIRAD (Centre de coopération internationale en recherche agronomique pour le développement – French Agricultural Research Centre for International Development) & AFZ (Association Française de Zootechnie – French Association for Animal Production).** n.d. The INRAE–CIRAD–AFZ tables [Cited 21 March 2025]. https://www.feedtables.com/content/tables

**IWTO (International Wool Textile Organisation).** 2021. *World sheep numbers & wool production*. IWTO market information, edition no. 17. https://iwto.org/wp-content/uploads/2022/04/IWTO-Market-Information-Sample-Edition-17.pdf

**Issa, I., Delbrück, S. & Hamm, U.** 2019. Bioeconomy from experts' perspectives – Results of a global expert survey. *PLoSOne*, 14(5): e0215917. https://doi.org/10.1371/journal.pone.0215917

**Javourez, U., O'Donohue, M. & Hamelin, L.** 2021. Waste-to-nutrition: A review of current and emerging conversion pathways. *Biotechnology Advances*, 53, 107857. https://doi.org/10.1016/j.biotechadv.2021.107857

**Jensen, L.S.** (2013a). Animal Manure Fertiliser Value, Crop utilisation and soil quality impacts. In: S.G. Sommer, M.L. Christensen, T. Schmidt & L.S. Jensen, eds. *Animal manure recycling: Treatment and management*, pp. 295–328. Hoboken, USA, Wiley. https://doi.org/10.1002/9781118676677.ch15

**Jensen, L.S.** 2013b. Animal manure residue upgrading and nutrient recovery in biofertilisers. In: S.G. Sommer, M.L. Christensen, T. Schmidt & L.S. Jensen, eds. *Animal manure recycling: Treatment and management*, pp. 305–324. Hoboken, USA, Wiley. https://doi.org/10.1002/9781118676677.ch14

**Jeong, Y.W., Choi, S.K., Choi, Y.S. & Kim, S.J.** 2015. Production of biocrude-oil from swine manure by fast pyrolysis and analysis of its characteristics. *Renewable Energy*, 79, 14–19. https://doi.org/10.1016/j.renene.2014.08.041

**Jinno, C., He, Y., Morash, D., McNamara, E., Zicari, S., King, A., Stein, H.H. & Liu, Y.** 2018. Enzymatic digestion turns food waste into feed for growing pigs. *Animal Feed Science and Technology*, 242, 48–58. https://doi.org/10.1016/j.anifeedsci.2018.05.006

**Joly, G. & Nikiema, J.** 2019. *Global experiences on waste processing with black soldier fly (Hermetia illucens): From technology to business*. 62 pp. Colombo, IWMI (International Water Management Institute). https://doi.org/10.5337/2019.214

**Jones, M.C., Bernhardt, C.E., Krauss, K.W. & Noe, G.B.** 2017. The Impact of late Holocene land use change, climate variability, and sea level rise on carbon storage in tidal freshwater wetlands on the southeastern United States coastal plain. *Journal of Geophysical Research: Biogeosciences*, 122(12): 3126–3141. https://doi.org/10.1002/2017JG004015

**Joseph, K. & Nithya, N.** 2009. Material flows in the lifecycle of leather. *Journal of Cleaner Production*, 17(7): 676-682. https://doi.org/10.1016/j.jclepro.2008.11.018

**Joseph, S., Cowie, A.L., Van Zwieten, L., Bolan, N., Budai, A., Buss, W., Cayuela, M.L., Graber, E.R., Ippolito, J.A., Kuzyakov, Y. & Luo, Y.** 2021. How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar. *Global Change Biology Bioenergy*, 13(11): 1731-1764. https://doi.org/10.1111/gcbb.12885

**Joshi, H.C., Kalra, N., Chaudhary, A. & Deb, D.L.** 1994. Environmental issues related with distillery effluent utilization in agriculture in India. *Asia Pacific Journal of Environment Ecology and Sustainable Development*, 1, 92–103.

**Jupp, A.R., Beijer, S., Narain, G.C., Schipper, W. & Slootweg, J.C.** 2021. Phosphorus recovery and recycling – closing the loop. *Chemical Society Reviews*, 50(1): 87–101. https://doi.org/10.1039/D0CS01150A

**Jurgilevich, A., Birge, T., Kentala-Lehtonen, J., Korhonen-Kurki, K., Pietikäinen, J., Saikku, L. & Schösler, H.** 2016. Transition towards circular economy in the food system. *Sustainability*, 8(1): 69. https://doi.org/10.3390/su8010069

**Kanagaraj, J., Senthilvelan, T., Panda, R.C. & Kavitha, S.** 2015. Eco-friendly waste management strategies for greener environment towards sustainable development in leather industry: A comprehensive review. *Journal of Cleaner Production*, 89, 1–17. https://doi.org/10.1016/j.jclepro.2014.11.013

**Kandyliari, A., Mallouchos, A., Papandroulakis, N., Golla, J.P., Lam, T.T., Sakellari, A., Karavoltsos, S., Vasiliou, V. & Kapsokefalou, M.** 2020. Nutrient composition and fatty acid and protein profiles of selected fish by-products. *Foods*, 9(2): 190. https://doi.org/10.3390/foods9020190

**Kang, J. & Wen, Z.** 2015. Use of microalgae for mitigating ammonia and $CO_2$ emissions from animal production operations – Evaluation of gas removal efficiency and algal biomass composition. *Algal Research*, 11, 204–210. https://doi.org/10.1016/j.algal.2015.06.020

**Kao, P.T., Darch, T., McGrath, S.P., Kendall, N.R., Buss, H.L., Warren, H. & Lee, M.R.F.** 2020. Factors influencing elemental micronutrient supply from pasture systems for grazing ruminants. In: D.L. Sparks, ed. *Advances in Agronomy*, pp. 161–229). Amsterdam, Elsevier. https://doi.org/10.1016/bs.agron.2020.06.004

**Kao, P.-T., Buss, H. L., McGrath, S. P., Darch, T., Warren, H. E. & Lee, M.R.F.** 2023. The uptake of selenium by perennial ryegrass in soils of different organic matter contents receiving sheep excreta. *Plant and Soil*, *486*(1–2): 639–659. https://doi.org/10.1007/s11104-023-05898-8

**Karlis, P., Presicce, F., Giner, S.G., Brinkmann, T. & Roudier, S.** 2024. *Best Available Techniques (BAT) reference document for the slaughterhouses, animal by-products and/or edible co-products industries*. In: *Publications Office of the European Union*. Brussels, European Union. https://doi.org/10.2760/18199

**Karlsson, J.O., Parodi, A., Van Zanten, H.H.E., Hansson, P.-A. & Röös, E.** 2020. Halting European Union soybean feed imports favours ruminants over pigs and poultry. *Nature Food*, 2(1): 38–46. https://doi.org/10.1038/s43016-020-00203-7

**Karlsson Potter, H. & Röös, E.** 2021. Multi-criteria evaluation of plant-based foods – Use of environmental footprint and LCA data for consumer guidance. *Journal of Cleaner Production*, 280(part 1): 124721. https://doi.org/10.1016/j.jclepro.2020.124721

**Kasapidou, E., Sossidou, E. & Mitlianga, P.** 2015. Fruit and vegetable co-products as functional feed ingredients in farm animal nutrition for improved product quality. *Agriculture*, 5(4): 1020–1034. https://doi.org/10.3390/agriculture5041020

**Kaur, P. & Purewai, S.S.** 2019. Biofertilizers and their role in sustainable agriculture. In: B. Giri, R.P. Ajit Varma, Q.-S. Wu, eds. *Biofertilizers for Sustainable Agriculture and Environment*, pp. 285–300. https://doi.org/10.1007/978-3-030-18933-4_12

**Kaur, T.** 2020. Vermicomposting: An effective option for recycling organic wastes. In: S.K. Das, ed. *Organic agriculture*, pp. 1–17. http://dx.doi.org/10.5772/intechopen.91892

**Kennedy, L.J., Ratnaji, T., Konikkara, N. & Vijaya, J.J.** 2018. Value added porous carbon from leather wastes as potential supercapacitor electrode using neutral electrolyte. *Journal of Cleaner Production*, 197(part 1): 930–936. https://doi.org/10.1016/j.jclepro.2018.06.244

**Kherdekar, G. & Adivarekar, R.V.** 2016. Dry scouring of wool. *International Journal of Exploring Emerging Trends in Engineering*, 3(6): 343–345. [Cited 30 June 2025]. https://www.academia.edu/30808469/DRY_SCOURING_OF_WOOL

**Kholif, A.E.** 2019. Glycerol use in dairy diets: A systemic review. *Animal Nutrition*, 5(3): 209–216. https://doi.org/10.1016/j.aninu.2019.06.002

**Khoshnevisan, B., Duan, N., Tsapekos, P., Awasthi, M.K., Liu, Z., Mohammadi, A., Angelidaki, I., Tsang, D.C.W., Zhang, Z., Pan, J., Ma, L., Aghbashlo, M., Tabatabaei, M. & Liu, H**. 2021. A critical review on livestock manure biorefinery technologies: Sustainability, challenges, and future perspectives. *Renewable and Sustainable Energy Reviews*, 135, 110033. http://dx.doi.org/10.1016/j.rser.2020.110033

**Kim, I., Ferket, P., Powers, W., Stein, H. & Kempen, T.** 2004. Effects of different dietary acidifier sources of calcium and phosphorus on ammonia, methane and odorant emission from growing-finishing pigs. *Animal Bioscience*, 17(8): 1131–1138. http://dx.doi.org/10.5713/ajas.2004.1131

**Kılıç, E., McLaren, S.J., Holmes, G., Fullana-i-Palmer, P. & Puig, R.** 2023. Product environmental footprint of New Zealand leather production. *The International Journal of Life Cycle Assessment*, 28(4): 349–366. http://dx.doi.org/10.1007/s11367-023-02143-3

**Klöpffer, W.** 2006. The hitch hiker´s guide to LCA – An orientation in LCA methodology and application. *The International Journal of Life Cycle Assessment*, 11(2): 142–142. https://doi.org/10.1065/lca2006.02.008

**Kleinschmit, D., Arts, B., Giurca, A., Mustalahti, I., Sergent, A. & Pülzl, H.** 2017. Environmental concerns in political bioeconomy discourses. *International Forestry Review*, 19(1): 41–55. http://dx.doi.org/10.1505/146554817822407420

**Koide, S.S.** 1998. Chitin-chitosan: Properties, benefits and risks. *Nutrition Research,* 18(6): 1091–1101. https://doi.org/10.1016/S0271-5317(98)00091-8

**Komiyama, T., Ito, T. & Saigusa, M.** 2014. Effects of phosphorus-based application of animal manure compost on the yield of silage corn and on soil phosphorus accumulation in an upland Andosol in Japan. *Soil Science and Plant Nutrition*, 60(6): 863–873. https://doi.org/10.1080/00380768.2014.955449

**Kopainsky, B. & Kapmeier, F.** 2023. Dynamic implications of the biological link between bovine milk and meat production for operationalizing the planetary health diet. *Nature Food*, 4, 1070–1074. https://doi.org/10.1038/s43016-023-00883-x

**Koppelmäki, K., Helenius, J. & Schulte, R.P.O.** 2021. Nested circularity in food systems: A Nordic case study on connecting biomass, nutrient and energy flows from field scale to continent. *Resources, Conservation and Recycling*, 164, 105218. https://doi.org/10.1016/J.RESCONREC.2020.105218

**Krausmann, F., Erb, K.-H., GinGrich, S. & Haberl, H.** 2013. Global human appropriation of net primary production doubled in the 20th century. *Proceedings of the National Academy of Sciences of the United States of America,* 110, 10324–10329. https://doi.org/10.1073/pnas.1211349110

**Kühnel, S., Schols, H.A. & Gruppen, H.** 2011. Aiming for the complete utilization of sugar-beet pulp: Examination of the effects of mild acid and hydrothermal pretreatment followed by enzymatic digestion. *Biotechnology for Biofuels*, 4(14): 1–14 https://doi.org/10.1186/1754-6834-4-14

**Kumaragamage, D. & Akinremi, O.O.** 2018. Manure phosphorus: Mobility in soils and management strategies to minimize losses. *Current Pollution Reports*, 4(2): 162–174. https://doi.org/10.1007/s40726-018-0084-x

**Kumari, S., Pishgar, S., Schwarting, M.E., Paxton, W.F. & Spurgeon, J.M.** 2018. Synergistic plasma-mediated electrochemical reduction of nitrogen to ammonia. *Chemical Communications*, 54(95): 13347–13350. https://doi.org/10.1039/C8CC07869F

**Kunasta, T. & Xia, X.** 2022. A review on anaerobic digestion with focus on the role of biomass co-digestion, modelling and optimisation on biogas production and enhancement. *Bioresource Technology*, 344(Part B): 126311. https://www.sciencedirect.com/science/article/pii/S0960852421016539

**Kupper, T., Bonjour, C. & Menzi, H.** 2015. Evolution of farm and manure management and their influence on ammonia emissions from agriculture in Switzerland between 1990 and 2010. *Atmospheric Environment*, 103, 215–221. https://doi.org/10.1016/j.atmosenv.2014.12.024

**Kupper, T., Häni, C., Neftel, A., Kincaid, C., Bühler, M., Amon, B. & VanderZaag, A.** 2020. Ammonia and greenhouse gas emissions from slurry storage – A review. *Agriculture, Ecosystems & Environment*, 300, 106963. https://doi.org/10.1016/j.agee.2020.106963

**Kurtzman, C.P. & Robnett, C.J.** 2003. Phylogenetic relationships among yeasts of the "Saccharomyces complex" determined from multigene sequence analyses. *FEMS Yeast Research*, 3(4): 417–432. https://doi.org/10.1016/S1567-1356(03)00012-6

**Kytta, V., Helenius, J. & Tuomisto, H.L.** 2021. Carbon footprint and energy use of recycles fertilizers in arable farming. *Journal of Cleaner Production*, 287, 125063. https://doi.org/10.1016/j.jclepro.2020.125063

**Lähteenmäki-Uutela, A., Rahikainen, M., Lonkila, A. & Yang, B.** 2021. Alternative proteins and EU food law. *Food Control*, 130, 108336. https://doi.org/10.1016/j.foodcont.2021.108336

**Lamolinara, B., Pérez-Martínez, A., Guardado-Yordi, E., Fiallos, C.G., Diéguez-Santana, K. & Ruiz-Mercado, G.J.** 2022. Anaerobic digestate management, environmental impacts, and techno-economic challenges. *Waste Management*, 140, 14–30. https://doi.org/10.1016/j.wasman.2021.12.035

**Lassaletta, L., Estellés, F., Beusen, A.H., Bouwman, L., Calvet, S., Van Grinsven, H.J., Doelman, J.C., Stehfest, E., Uwizeye, A. & Westhoek, H.** 2019. Future global pig production systems according to the Shared Socioeconomic Pathways. *Science of the Total Environment*, 665, 739–751. https://doi.org/10.1016/j.scitotenv.2019.02.079

**Latka, C., Parodi, A., Van Hal, O., Heckelei, T., Leip, A., Witzke, H.-P. & Van Zanten, H.H.E.** 2022. Competing for food waste – Policies' market feedbacks imply sustainability tradeoffs. *Resources, Conservation and Recycling*, 186, 106545. https://doi.org/10.1016/j.resconrec.2022.106545

**Leach, R.M.** 1982. Biochemistry of the organic matrix of the eggshell. *Poultry Science*, 61(10): 2040–2047. https://doi.org/10.3382/ps.0612040

**Leather International.** 2023. China 2022 leather exports up by almost 20%. *Leather International*, 21 March 2023. London, Global Trade Media. [Cited 30 June 2025]. https://www.leathermag.com/news/china-2022-leather-exports-up-by-almost-20-10691234/

**Lebacq, T., Baret, P.V. & Stilmant, D.** 2013. Sustainability indicators for livestock farming. A review. *Agronomy for Sustainable Development*, 33(2): 311–327. https://doi.org/10.1007/s13593-012-0121-x

**Lee, M.R.F., Tichit, M., Domingues, J.P., McAuliffe, G.A. & Takahashi, T.** 2021. Nutrient provision capacity of alternative livestock farming systems per area of arable farmland required. *Scientific Reports*, 11, 14975. https://doi.org/10.1038/s41598-021-93782-9

**Leip, A., Ledgard, S., Uwizeye, A., Palhares, J.C.P., Aller, M.F., Amon, B., Binder, M., Cordovil, C.M.s.S., De Camillis, C., Dong, H., Fusi, A., Helin, J., Hörtenhuber, S., Hristov, A.N., Koelsch, R., Liu, C., Masso, C., Nkongolo, N.V., Patra, A K., Redding, M.R. & Wang, Y.** 2019. The value of manure – Manure as co-product in life cycle assessment. *Journal of Environmental Management*, 241, 293–304. https://doi.org/10.1016/j.jenvman.2019.03.059

**Leiva, A., Granados-Chinchilla, F., Redondo-Solano, M., Arrieta-González, M., Pineda-Salazar, E. & Molina, A.** 2018. Characterization of the animal by-product meal industry in Costa Rica: Manufacturing practices through the production chain and food safety. *Poultry Science*, 97(6): 2159–2169. https://doi.org/10.3382/ps/pey058

**Li, H., Lu, J., Zhang, Y. & Liu, Z.** 2018. Hydrothermal liquefaction of typical livestock manures in China: Biocrude oil production and migration of heavy metals. *Journal of Analytical and Applied Pyrolysis*, 2018(135): 133–140. http://dx.doi.org/10.1016/j.jaap.2018.09.010

**Li, M.H., Robinson, E.H., Oberle, D.F., Lucas, P.M. & Bosworth, B.G.** 2012. Evaluation of corn gluten feed and cottonseed meal as partial replacements for soybean meal and corn in diets for pond-raised hybrid catfish, *Ictalurus punctatus* × *I. furcatus*. *Journal of the World Aquaculture Society*, 43(1): 107–113. https://doi.org/10.1111/j.1749-7345.2011.00542.x

**Li, X.** 2011. Rural organic waste treatment system design and analysis based on vermicomposting technology. Stockholm, KTH Royal Institute of Technology. Master's thesis. https://www.diva-portal.org/smash/record.jsf?pid=diva2:580002

**Likiliki, C., Convers, B. & Beline, F.** 2020. Dataset on the characteristics of the liquid effluent issued from separation of faeces and urine under slats using V-shaped scraper in swine buildings. *Data in Brief*, 30, 105533. https://doi.org/10.1016/j.dib.2020.105533

**Lima, P. de Mello Tavares, Oliveira, P. Batelli, Campeche, A., Moreira, G. Dias, Paim, T. do Prado, McManus, C., Abdalla, A.L., Dantas, A.M. Morais, De Souza, J. Rodrigues & Louvandini, H.** 2014. Methane emission of Santa Inês sheep fed cottonseed by-products containing different levels of gossypol. *Tropical Animal Health and Production*, 46(1): 285–288. https://doi.org/10.1007/s11250-013-0491-3

**Lin, L., Xu, F., Ge, X. & Li, Y.** 2018. Improving the sustainability of organic waste management practices in the food-energy-water nexus: A comparative review of anaerobic digestion and composting. *Renewable and Sustainable Energy Reviews*, 89, 151–167. https://doi.org/10.1016/j.rser.2018.03.025

**Linder, M., Sarasini, S. & Van Loon, P.** 2017. A metric for quantifying product-level circularity. *Journal of Industrial Ecology*, 21(3): 545–558. https://doi.org/10.1111/jiec.12552

**Liu, J., Spargo, J.T., Kleinman, P.J.A., Meinen, R., Moore, P.A. & Beegle, D.B.** 2018. Water-extractable phosphorus in animal manure and manure compost: Quantities, characteristics, and temporal changes. *Journal of Environmental Quality*, 47(3): 471–479. https://doi.org/10.2134/jeq2017.12.0467

**Liu, Y., Tang, R., Li, L., Zheng, G., Wang, J., Wang, G., Bao, Z., Yin, Z., Li, G. & Yuan, J.** 2023. A global meta-analysis of greenhouse gas emissions and carbon and nitrogen losses during livestock manure composting: Influencing factors and mitigation strategies. *Science of The Total Environment*, 885, 163900. https://doi.org/10.1016/j.scitotenv.2023.163900

**Liu, Z., Zhu, H., Wang, B. & Zhang, Y.** 2009. Effect of ratios of manure to crop on dry anaerobic digestion for biogas production. *Nongye Gongcheng Xuebao/Transactions of the Chinese Society of Agricultural Engineering*, 25(4): 196–200. [Cited 30 June 2025]. http://www.tcsae.org/en/article/id/20090437

**Lopez-Ridaura, S., Van Der Werf, H., Paillat, J.M. & Le Bris, B.** 2009. Environmental evaluation of transfer and treatment of excess pig slurry by life cycle assessment. *Journal of Environmental Management*, 90(2): 1296–1304. https://doi.org/10.1016/j.jenvman.2008.07.008

**Loyon, L.** 2017. Overview of manure treatment in France. *Waste Management*, 61, 516–520. https://doi.org/10.1016/j.wasman.2016.11.040

**Lunsin, R., Duanyai, S., Pilajun, R., Duanyai, S. & Sombatsri, P.** 2018. Effect of urea- and molasses-treated sugarcane bagasse on nutrient composition and in vitro rumen fermentation in dairy cows. *Agriculture and Natural Resources*, 52(6): 622–627. https://doi.org/10.1016/j.anres.2018.11.010

**Lynch, K.M., Steffen, E.J. & Arendt, E.K.** 2016. Brewers' spent grain: A review with an emphasis on food and health. *Journal of the Institute of Brewing*, 122(4): 622–627. https://doi.org/10.1002/jib.363

**Lyu, G., Wu, S. & Zhang, H.** 2015. Estimation and comparison of bio-oil components from different pyrolysis conditions. *Frontiers in Energy Research*, 3, article 28. https://doi.org/10.3389/fenrg.2015.00028

**MacGarr Rabinowitz, P., Pappaioanou, M., Bardosh, K. L. & Conti, L.** 2018. A planetary vision for one health. *BMJ Global Health*, 3(5): e001137. https://doi.org/10.1136/bmjgh-2018-001137

**Macwan, S.R., Dabhi, B.K., Parmar, S.C. & Aparnathi, K.D.** 2016. Whey and its utilization. *International Journal of Current Microbiology and Applied Sciences*, 5(8): 134–155. https://doi.org/10.20546/ijcmas.2016.508.016

**Madelrieux, S., Courtonne, J.Y., Grillot, M. & Harchaoui, S.** 2022. Bioéconomie et économie circulaire: Lecture critique et place de l'élevage. *INRAE Productions Animales*, 36(1): 1–15. https://dx.doi.org/10.20870/productions-animales.2023.36.1.7430

**Magan, N. & Aldred, D.** 2007. Post-harvest control strategies: Minimizing mycotoxins in the food chain. *International Journal of Food Microbiology*, 119(1–2): 131–139. https://doi.org/10.1016/j.ijfoodmicro.2007.07.034

**Majluf, P., Matthews, K., Pauly, D., Skerritt, D.J. & Palomares, M.L.D.** 2024. A review of the global use of fishmeal and fish oil and the Fish In:Fish Out metric. *Science Advances*, 10(42): eadn5650. https://doi.org/10.1126/sciadv.adn5650

**Makamure, F., Mukmba, P. & Makaka, G.** 2021. An analysis of bio-digester substrate heating methods: A review. *Renewable and Sustainable Energy Reviews*, 137, 110432. https://doi.org/10.1016/j.rser.2020.110432

**Makkar, S., Rath, N.C., Packialakshimi, B., Huff, W.E. & Huff, G.R.** 2015. Nutritional effects of egg shell membrane supplements on chicken performance and immunity. *Poultry Science*, 94(6): 1184–1189. https://doi.org/10.3382/ps/pev098

**Malisch, R.** 2017. Incidents with dioxins and PCBs in food and feed investigative work, risk management and economic consequences. *Journal of Environmental Protection*, 8, 744–785. http://dx.doi.org/10.4236/jep.2017.86048

**Mallory, E.B. & Griffin, T.S.** 2007. Impacts of soil amendment history on nitrogen availability from manure and fertilizer. *Soil Science Society of America Journal*, 71(3): 964–973. https://doi.org/10.2136/sssaj2006.0244

**Manzano, P., Rowntree, J., Thompson, L., Del Prado, A., Ederer, P., Windisch, W. & Lee, M.R.F.** 2023. Challenges for the balanced attribution of livestock's environmental impacts: The art of conveying simple messages around complex realities. *Animal Frontiers*, 13(2): 35–44. https://doi.org/10.1093/af/vfac096

**Marazzi, F., Sambusiti, C., Monlau, F., Cecere, S.E., Scaglione, D., Barakat, A., Mezzanotte, V. & Ficara, E.** 2017. A novel option for reducing the optical density of liquid digestate to achieve a more productive microalgal culturing. *Algal Research*, 24(part A), 19–28. https://doi.org/10.1016/j.algal.2017.03.014

**Marchbank, T., Elia, G. & Playford, R.J.** 2009. Intestinal protective effect of a commercial fish protein hydrolysate preparation. *Regulatory Peptides*, 155(1–3): 105–109. https://doi.org/10.1016/j.regpep.2009.02.003

**Marchuk, S., Tait, S., Sinha, P., Harris, P., Antille, D.L. & McCabe, B.K.** 2023. Biosolids-derived fertilisers: A review of challenges and opportunities. *Science of The Total Environment*, 875, 162555. https://doi.org/10.1016/j.scitotenv.2023.162555

**Martinez-Alvarez, O., Chamorro, S. & Brenes, A.** 2015. Protein hydrolysates from animal processing by-products as a source of bioactive molecules with interest in animal feeding: A review. *Food Research International*, 73, 204–212. https://doi.org/10.1016/j.foodres.2015.04.005

**Mateos, G.G., Camara, L., Fondevila, G. & Lazaro, R.P.** 2019. Critical review of the procedures used for estimation of the energy content of diets and ingredients in poultry. *Journal of Applied Poultry Research*, 28(3): 506–525. https://doi.org/10.3382/japr/pfy025

**Mazac, R., Järviö, N. & Tuomisto, H.L.** 2023. Environmental and nutritional Life Cycle Assessment of novel foods in meals as transformative food for the future. *Science of The Total Environment*, 876, 162796. https://doi.org/10.1016/j.scitotenv.2023.162796

**Mažeikienž, R. & Bleizgys, R.** 2022. Use of bio-preparations to reduce ammonia emissions from cattle farming: Effects of manure storage time and ventilation intensity. *Agriculture*, 12(10): 1626. https://doi.org/10.3390/agriculture12101626

**McAuliffe, G.A., Takahashi, T. & Lee, M.R.F.** 2020. Applications of nutritional functional units in commodity-level life cycle assessment (LCA) of agri-food systems. *International Journal of Life Cycle Assessment*, 25, 208–221. https://doi.org/10.1007/s11367-019-01679-7

**McCormick, K. & Kautto, N.** 2013. The bioeconomy in Europe: An overview. *Sustainability*, 5(6): 2589–2608. https://doi.org/10.3390/su5062589

**McCormick, R.L., Graboski, M.S., Alleman, T.L., Herring, A.M. & Tyson, K.S.** 2001. Impact of biodiesel source material and chemical structure on emissions of criteria pollutants from a heavy-duty engine. *Environmental Science & Technology*, 35(9): 1742–1747. https://doi.org/10.1021/es001636t

**McGlade, J., Palahi, M., Costanza, R., Trebeck, K., Fiaromonti, L., Lovins, L.H., Wallis, S., Pickett, K. & Wilkinson, R.** 2020. *Investing in nature to transform the post COVID-19 economy: A 10-point action plan to create a circular bioeconomy devoted to sustainable wellbeing*. 11 (2). https://discovery.ucl.ac.uk/id/eprint/10108755/1/Palahi%2C%20M%202020%20Investing%20in%20Nature%20and%20the%20Circular%20Bioeconomy.pdf

**MDS (Ministero de Desarollo Social Paraguay).** 2024. Hay 6.109.644 habitantes en Paraguay, según resultados preliminares del Censo Nacional. In: *MDS*. Fernando de la Mora, Paraguay. [Cited 30 June 2025]. https://www.mds.gov.py/index.php/noticias/hay-6109644-habitantes-en-paraguay-segun-resultados-preliminares-del-censo-nacional

**Meegoda, J.N., Li, B., Patel, K. & Wang, L.B.** 2018. A review of the processes, parameters, and optimization of anaerobic digestion. *International Journal of Environmental Research and Public Health.*, 15(10): 2224. https://doi.org/10.3390/ijerph15102224

**Meinlschmidt, P., Ueberham, E., Lehmann, J., Schweiggert-Weisz, U. & Eisner,.P.** 2016. Sensory and physicochemical properties of fermented soy protein isolate. *Food Chemistry*, 205(8): 229–238. https://doi.org/10.1016/j.foodchem.2016.03.016

**Mengistu, A.G., Tesfuhuney, W.A., Woyessa, Y.E., Ejigu, A.A. & Alemu, M.D.** 2025. Contrasting hydro-climatic trends and drought dynamics in Ethiopia and South Africa under climate change. *Climate Dynamics*, 63(2): 105. https://doi.org/10.1007/s00382-025-07588-w

**Menzi, H., Oenema, O., Burton, C., Shipin, O., Gerber, P., Robinson, T. & Franceschini, G.** 2010. Impacts of intensive livestock production and manure management on the environment. In: H. Steinfeld, H.A. Mooney, F. Schneider & L.E. Neville, eds. *Livestock in a Changing Landscape: Drivers, Consequences, and Responses*, vol. 1, pp. 139–163. Washington, DC., Island Press. https://openknowledge.fao.org/server/api/core/bitstreams/10826b4b-148d-4f64-8bfd-2a8ec97e3917/content

**MIA (Meat Industry Association of New Zealand).** 2022. *Meat Industry Association Annual Report 2022*. 62 pp. Wellington, MIA. https://mia.co.nz/wp-content/uploads/2023/09/MIA-Annual-Report-2022.pdf

**Michalovicz, L., Dick, W.A., Cervi, E.C., Tormena, C.A. & Müller, M.M.L.** 2017. Flue gas desulfurization gypsum as a chemical amendment to reduce the concentrations of phosphorus and suspended solids in liquid manure. *Management of Environmental Quality: An International Journal*, 28(5): 624–631. https://doi.org/10.1108/MEQ-09-2015-0172

**Mills, S., Ross, R.P., Hill, C., Fitzgerald, G.F. & Stanton, C.** 2011. Milk intelligence: Mining milk for bioactive substances associated with human health. *International Dairy Journal*, 21(6): 377–401. https://doi.org/10.1016/j.idairyj.2010.12.011

**Milu, M.S., Hashem, M.A., Payel, S. & Hasan, M.A.** 2022. Leather buffing dust in brick production: Solid waste management in tanneries. *Case Studies in Construction Materials*, 17, e01625. https://doi.org/10.1016/j.cscm.2022.e01625

**Mobashar, M., Hummel, J., Blank, R. & Südekum, K.H.** 2010. Ochratoxin A in ruminants – A review on its degradation by gut microbes and effects on animals. *Toxins (Basel)*, 2(4): 809–839. https://doi.org/10.3390/toxins2040809

**Moe, S.M.** 2008. Disorders involving calcium, phosphorus, and magnesium. *Primary Care: Clinics in Office Practice*, 35(2): 215–237. https://doi.org/10.1016/j.pop.2008.01.007

**Mohammadi Shad, Z., Venkitasamy, C. & Wen, Z.** 2021. Corn distillers dried grains with solubles: Production, properties, and potential uses. *Cereal Chemistry*, 98(5): 999–1019. https://doi.org/10.1002/CCHE.10445

**Mohsen, A.A. & Lovell, R.T.** 1990. Partial substitution of soybean meal with animal protein sources in diets for channel catfish. *Aquaculture*, 90(3–4): 303–311. https://doi.org/10.1016/0044-8486(90)90254-K

**Möller, K., Oberson, A., Bünemann, E.K., Cooper, J., Friedel, J.K., Glæsner, N., Hörtenhuber, S., Løes, A.-K., Mäder, P., Meyer, G., Müller, T., Symanczik, S., Weissengruber, L., Wollmann, I. & Magid, J.** 2018. Improved phosphorus recycling in organic farming: Navigating between constraints. In: D.L. Sparks, ed. *Advances in Agronomy*, pp. 159–237. Amsterdam, Elsevier. https://doi.org/10.1016/bs.agron.2017.10.004

**Monteny, G.J.** 2000. *Modelling of ammonia emissions from dairy cow houses*. Wageningen, Kingdom of the Netherlands, Wageningen University. PhD dissertation.

**Mordenti, A.L., Giaretta, E., Campidonico, L., Parazza, P. & Formigoni, A.** 2021. A review regarding the use of molasses in animal nutrition. *Animals*, 11(1): 115. https://doi.org/10.3390/ani11010115

**Morey, L., Fernández, B., Tey, L., Biel, C., Robles-Aguilar, A., Meers, E., Soler, J., Porta, R., Cots, M. & Riau, V.** 2023. Acidification and solar drying of manure-based digestate to produce improved fertilizing products. *Journal of Environmental Management*, 336, 117664. https://doi.org/10.1016/j.jenvman.2023.117664

**Mottet, A., De Haan, C., Falcucci, A., Rempio, G., Opio, C. & Gerber,** P. 2017. Livestock: On our plates or eating at our table? A new analysis of the feed/food debate. *Global Food Security*, 14, 1–8. https://doi.org/10.1016/j.gfs.2017.01.001

**Moutinho, S., Martinez-Llorens, S., Tomás-Vidal, A. & Jover-Cerdá, M.O.T.** 2017. Meat and bone meal as partial replacement for fish meal in diets for gilthead seabream (*Sparus aurata*) juveniles: Growth, feed efficiency, amino acid utilization, and economic efficiency. *Aquaculture*, 468(1): 271–277. https://doi.org/10.1016/j.aquaculture.2016.10.024

**Muoghalu, C.C., Owusu, P.A., Lebu, S., Nakagiri, A., Semiyaga, S., Iorhemen, O.T. & Manga, M.** 2023. Biochar as a novel technology for treatment of onsite domestic wastewater: A critical review. *Frontiers in Environmental Science*, 11, 1095920. https://doi.org/10.3389/fenvs.2023.1095920

**Muralidharan, V., Palanivel, S. & Balaraman, M.** 2022. Turning problem into possibility: A comprehensive review on leather solid waste intra-valorization attempts for leather processing. *Journal of Cleaner Production*, 367, 133021. https://doi.org/10.1016/j.jclepro.2022.133021

**Murphy, D.P., O'Doherty, J.V., Boland, T.M., O'Shea, C.J., Callan, J.J., Pierce, K.M. & Lynch, M.B.** 2011. The effect of benzoic acid concentration on nitrogen metabolism, manure ammonia and odour emissions in finishing pigs. *Animal Feed Science and Technology*, 163(2–4): 194–199. https://doi.org/10.1016/j.anifeedsci.2010.10.009

**Muscat, A., De Olde, E.M., Zokavic, Z., De Boer, I.J.M. & Ripoll-Bosch, R.** 2021. Food, energy or biomaterials? Policy coherence across agro-food and bioeconomy policy domains in the EU. *Environmental Science and Policy*, 123, 21–30. https://doi.org/10.1016/j.envsci.2021.05.001

**Mwangi, M. & Kariuki, S.** 2015. Factors determining adoption of new agricultural technology by smallholder farmers in developing countries. *Journal of Economics and Sustainable Development*, 6, 208–216. https://www.semanticscholar.org/paper/Factors-Determining-Adoption-of-New-Agricultural-by-Mwangi-Kariuki/eca8dfae841267e19a8d13a53fd19f33a651e347

**Naghdi, S., Rezaei, M., Heidari, M.G., Tahergorabi, R., Lorenzo, J.M. & Mirzaei, F.** 2024. Insights into fishery by-product application in aquatic feed and food: A review. *Aquaculture International*, 32(5): 5851–5910. https://doi.org/10.1007/s10499-024-01447-x

**Nana, P., Kimpara, J.M., Tiambo, C.K., Tiogue, C.T., Youmbi, J., Choundong, B. & Fonkou, T.** 2018. Black soldier flies (*Hermetia illucens* Linnaeus) as recyclers of organic waste and possible livestock feed. *International Journal of Biological and Chemical Sciences*, 12(5): 1930–1943. https://doi.org/10.4314/ijbcs.v12i5.4

**NARA (North American Renderers Association).** 2020. Sustainability of rendering. In: *NARA*. Alexandria, USA. **[Cited 30 June 2025]. https://nara.org/sustainability/**

**Nastasijevic, I., Boskovic, M. & Glisic, M.** 2023. Abattoir hygiene. In: M.E. Knowles, M., L.E. Anelich, A.R. Boobis &. B. Popping, eds. *Present knowledge in food safety: A risk-based approach through the food chain*, pp. 412–438. Colleyville, USA, Knowles.

**Nautiyal, M., Hunting, A., Joseph, F. & Cleveland, D.** 2023. Examining practices of apparel use and end of life in New Zealand. *Sustainability*, 15(6): 5141. https://doi.org/10.3390/su15065141

**Ndambi, O.A., Pelster, D.E., Owino, J.O., De Buisonjé, F. & Vellinga, T.** 2019. Manure management practices and policies in sub-Saharan Africa: Implications on manure quality as a fertilizer. *Frontiers in Sustainable Food Systems*, 3, 29. https://doi.org/10.3389/fsufs.2019.00029

**Nega, T.** 2018. Review on nutritional limitations and opportunities of using rapeseed meal and other rape seed by-products in animal feeding. *Journal of Nutritional Health & Food Engineering*, 8(1): 43–48. https://doi.org/10.15406/jnhfe.2018.08.00254

**Neme, K. & Mohammed, A.** 2017. Mycotoxin occurrence in grains and the role of postharvest management as a mitigation strategies. A review. *Food Control*, 78, 412–425. https://doi.org/10.1016/j.foodcont.2017.03.012

**Nevens, F., Verbruggen, I., Reheul, D. & Hofman, G.** 2006. Farm gate nitrogen surpluses and nitrogen use efficiency of specialized dairy farms in Flanders: Evolution and future goals. *Agricultural Systems*, 88(2–3): 142–155. https://doi.org/10.1016/j.agsy.2005.03.005

**Newton, R.W., Maiolo, S., Malcorps, W. & Little, D.C.** 2023. Life Cycle Inventories of marine ingredients. *Aquaculture*, 565, 739096. https://doi.org/10.1016/j.aquaculture.2022.739096

**Nicolai, R.E. & Lefers, R.M.** 2006. Biofilters used to reduce emissions from livestock housing – A literature review. Workshop on agricultural air quality, North Carolina State University: Raleigh, USA, No. 1460885. https://www.umad.de/infos/woaaq2006/posters-n-p.pdf

**Nkuna, R., Roopnarain, A., Rashama, C. & Adeleke, R.** 2022. Insights into organic loading rates of anaerobic digestion for biogas production: A review. *Critical Reviews in Biotechnology*, 42(4): 255–274. https://doi.org/10.1080/07388551.2021.1942778

**NRC (National Research Council).** 2001. *Nutrient requirements of dairy cattle*. Washington, DC., National Academies Press. https://doi.org/10.17226/9825

**NRC.** 2005. *Mineral tolerance of animals.* Washington, DC., National Academic Press. [Cited 19 July 2025]. https://nap.nationalacademies.org/catalog/11309/mineral-tolerance-of-animals-second-revised-edition-2005

**O'Brien, R.D., Jones, L.A., King, C.C., Wakelyn, P.J. & Wan, P.J.** 2005. Cottonseed oil. In: F. Shahidi, ed. *Bailey's industrial oil and fat products*, vol. 2, pp. 139–196. Hoboken, USA, Wiley. https://onlinelibrary.wiley.com/doi/book/10.1002/047167849X

**O'Callaghan, T.F.** 2022. Butter and buttermilk. In: P.L.H. McSweeney & J.P. McNamara, eds. *Encyclopedia of Dairy Sciences*, pp. 1–7. Amsterdam, Elsevier. https://doi.org/10.1016/B978-0-12-818766-1.00230-0

**Ockerman, H.W. & Basu, L.** 2014. BY-PRODUCTS | Inedible. In: M. Dikeman & C. Devine, eds. *Encyclopedia of Meat Sciences*, pp. 125–136. Amsterdam, Elsevier. https://doi.org/10.1016/B978-0-12-384731-7.00032-5

**OECD (Organisation for Economic Co-operation and Development).** 2018. Realising the circular bioeconomy. In: *OECD Science, Technology and Industry Policy Papers*. Paris, OECD. https://doi.org/10.1787/31bb2345-en

**OECD & FAO.** 2022. *OECD–FAO Agricultural Outlook 2022-2031*. Paris, OECD. https://doi.org/10.1787/f1b0b29c-en

**Oenema, O., Kros, H. & De Vries, W.** 2003. Approaches and uncertainties in nutrient budgets: Implications for nutrient management and environmental policies. *European Journal of Agronomy*, 20(1–2): 3–16. https://doi.org/10.1016/s1161-0301(03)00067-4

**Oke, I.A., Fasuyi-Enang, O., Oloyede, H.O., Obijole, O.A., Fehintola, E.O. & Amoko, J.S.** 2014. Adsorption kinetics of $Pb^{2+}$, $Ni^{2+}$, and $Cd^{2+}$ onto powdered eggshells. *Ife Journal of Science*, 18(2): 273–290. https://www.ajol.info/index.php/ijs/article/view/131773

**Ominski, K., McAllister, T., Stanford, K., Mengistu, G., Kebebe, E.G., Omonijo, F., Cordeiro, M., Legesse, G. & Wittenberg, K.** 2021. Utilization of by-products and food waste in livestock production systems: A Canadian perspective. *Animal Frontiers*, 11(2): 55–63. https://doi.org/10.1093/AF/VFAB004

**Ou, L., Li, S., Tao, L., Phillips, S., Hawkins, T., Singh, A., Snowden-Swan, L. & Cai, H.** 2022. Techno-economic analysis and Life-Cycle Analysis of renewable diesel fuels produced with waste feedstocks. *ACS Sustainable Chemistry & Engineering*, 10(1): 382–393. https://doi.org/10.1021/acssuschemeng.1c06561

**Owuamanam, S. & Cree, D.** 2020. Progress of bio-calcium carbonate waste eggshell and seashell fillers in polymer composites: A review. *Journal of Composites Science*, 4(2): 70. https://doi.org/10.3390/jcs4020070

**Pain, B. & Menzi, H., eds.** 2011. *Glossary of terms on livestock and manure management 2011*. Darmstadt, Germany, Association for Technology and Structures in Agriculture (KTBL). https://www.ktbl.de/fileadmin/user_upload/Allgemeines/Startseite/Englisch/Glossary_of_Terms.pdf

**Palmonari, A., Cavallini, D., Sniffen, C.J., Fernandes, L., Holder, P., Fagioli, L., Fusaro, I., Biagi, G., Formigoni, A. & Mammi, L.** 2020. Short communication: Characterization of molasses chemical composition. *Journal of Dairy Science*, 103(7): 6244–6249. https://doi.org/10.3168/jds.2019-17644

**Pan, D., Tang, J., Zhang, L., He, M. & Kung, C.-C.** 2021. The impact of farm scale and technology characteristics on the adoption of sustainable manure management technologies: Evidence from hog production in China. *Journal of Cleaner Production*, 280(part 1), 124340. https://doi.org/10.1016/j.jclepro.2020.124340

**Parsons, G.L., Shelor, M.K. & Drouillard, J.S.** 2009. Performance and carcass traits of finishing heifers fed crude glycerin. *Journal of Animal Science*, 87(2): 653–657. https://doi.org/10.2527/JAS.2008-1053

**Patel, A., Brahmbhatt, M., Bariya, A., Nayak, J. & Singh, V.** 2023. Blockchain technology in food safety and traceability concern to livestock products. *Heliyon*, *9*(6): e16526. https://doi.org/10.1016/j.heliyon.2023.e16526

**Paul, B.K., Butterbach-Bahl, K., Notenbaert, A., Nduah Nderi, A. & Ericksen, P.** 2020. Sustainable livestock development in low- and middle-income countries: Shedding light on evidence-based solutions. *Environmental Research Letters*, 16(1): 011001. https://doi.org/10.1088/1748-9326/abc278

**Pavlista, A.D. & Rush, I.G.** 2002. *EC02-152 – S value of potatoes for feeding livestock*. Extension circular No. 4764. University of Nebraska–Lincoln Extension. https://digitalcommons.unl.edu/extensionhist/4764

**Pecka-Kiełb, E., Zachwieja, A., Miśta, D., Zawadzki, W. & Zielak-Steciwko, A.** 2017. Use of corn dried distillers grains (DDGS) in feeding of ruminants. In: E. Jacob-Lopes & L. Queiroz Zepka, eds. *Frontiers in bioenergy and biofuels*, pp. 91-107. London, IntechOpen. http://dx.doi.org/10.5772/66357

**Pepper, I.L., Brooks, J.P. & Gerba, C.P.** 2019. Land application of organic residuals: Municipal biosolids and animal manures. In: M.L. Brusseau, I.L. Pepper & C.P. Gerba, eds. *Environmental and pollution science*, pp. 419–434. Amsterdam, Elsevier. https://doi.org/10.1016/B978-0-12-814719-1.00023-9

**Perera, M.K., Englehardt, J.D. & Dvorak, A.C.** 2019. Technologies for recovering nutrients from wastewater: A critical review. *Environmental Engineering Science*, 36(5): 511–529. https://doi.org/10.1089/ees.2018.0436

**Pérez-Aguilar, H., Lacruz-Asaro, M. & Arán-Ais, F.** 2022. Towards a circular bioeconomy: High added value protein recovery and recycling from animal processing by-products. *Sustainable Chemistry and Pharmacy*, 28, 100667. https://doi.org/10.1016/j.scp.2022.100667

**Periolatto, M. & Gozzelino, G.** 2015. Greasy raw wool for clean-up process of marine oil spill: From laboratory to scaled prototype. *Chemical Engineering Transactions*, 43, 2269–2274. http://dx.doi.org/10.3303/CET1543379

**Perry, B.D., Robinson, T.P. & Grace, D.C.** 2018. Review: Animal health and sustainable global livestock systems. *Animal*, 12(8): 1699–1708. https://doi.org/10.1017/S1751731118000630

**Piash, M.I., Uemura, K., Itoh, K. & Iwabuchi, K.** 2023. Meat and bone meal biochar can effectively reduce chemical fertilizer requirements for crop production and impart competitive advantages to soil. *Journal of Environmental Management*, 336, 117612. https://doi.org/10.1016/j.jenvman.2023.117612

**Pinotti, L., Luciano, A., Ottoboni, M., Manoni, M., Ferrari, L., Marchis, D. & Tretola, M.** 2021. Recycling food leftovers in feed as opportunity to increase the sustainability of livestock production. *Journal of Cleaner Production*, 294, 126290. https://doi.org/10.1016/j.jclepro.2021.126290

**Pintens, D.A., Shinners, K.J., Friede, J.C., Digman, M.F. & Kalscheur, K.F.** 2023. Impact–shredding processing of whole-plant corn: Machine performance, physical properties, and in situ ruminant digestion. *Agriculture*, 13(1): 160. https://doi.org/10.3390/agriculture13010160

**Pires, A.F., Marnotes, N.G., Rubio, O.D., Garcia, A.C. & Pereira, C.D.** 2021. Dairy by-products: A review on the valorization of whey and second cheese whey. *Foods*, 10(5): 1067. https://doi.org/10.3390/foods10051067

**Ponkham, W., Limroongreungrat, K. & Sangnark, A.** 2010. Extraction of collagen from egg shell membrane by using organic acids. *Thai Journal of Agricultural Science*, 44(5): 354–360. https://www.thaiscience.info/journals/Article/TJAS/10899309.pdf

**Potatoworld.** 2021. Starch processing and the role of starch potatoes in animal feed. *Potato World Magazine* blog, 16 August 2021 [Cited 23 July 2025]. https://blog.potatoworld.eu/starch-processing-and-the-role-of-starch-potatoes-in-animal-feed

**Powell, J.M., Gourley, C.J.P., Rotz, C.A. & Weaver, D.M.** 2010. Nitrogen use efficiency: A potential performance indicator and policy tool for dairy farms. *Environmental Science & Policy*, 13(3): 217–228. https://doi.org/10.1016/j.envsci.2010.03.007

**Priefer, C., Jörissen, J. & Frör, O.** 2017. Pathways to shape the bioeconomy. *Resources*, 6(1): 10. https://doi.org/10.3390/resources6010010

**Provolo, G., Perazzolo, F., Mattachini, G., Finzi, A., Naldi, E. & Riva, E.** 2017. Nitrogen removal from digested slurries using a simplified ammonia stripping technique. *Waste Management*, 69, 154–161. https://doi.org/10.1016/j.wasman.2017.07.047

**Puente-Rodríguez, D., Van Laar, H. & Veraart, M.** 2022. A circularity evaluation of new feed categories in The Netherlands – Squaring the circle: A review. *Sustainability*, 14(4): 2352. https://doi.org/10.3390/su14042352

**Pujari, M., Demeke, G., Worku, A. & Komarabathina, S.** 2023. Potentiality of tannery buffing chromium-containing solid waste in making concrete blocks. *Materials Today: Proceedings*, 80(part 2): 587–590. http://dx.doi.org/10.1016/j.matpr.2022.11.052

**Pusztai, A., Bardocz, S. & Martin-Cabrejas, M.A.** 2004. The mode of action of antinutritional factors (ANFs) on the gastrointestinal tract and its microflora. In: M. Muzquiz, C.G. Hill, M.M. Pedrosa & C. Burbano, eds. *Proceedings of the Fourth International Workshop on Antinutritional Factors in Legume Seeds and Oilseeds*, pp. 87–100. EAAP publication No. 110. Wageningen, Kingdom of the Netherlands, Wageningen Academic Publishers. https://doi.org/10.3920/978-90-8686-574-1_9

**Qadir, M., Drechsel, P., Jiménez Cisneros, B., Kim, Y., Pramanik, A., Mehta, P. & Olaniyan, O.** 2020. Global and regional potential of wastewater as a water, nutrient and energy source. *Natural resources forum*, 44(1): 40–51. https://doi.org/10.1111/1477-8947.12187

**Rafiq, S.M. & Rafiq, S.I.** 2019. Milk by-products utilization. In: S.A. Ibrahim, T. Zimmerman & R. Gyawali, eds. *Current issues and challenges in the dairy industry*, pp. 31–38. London, IntechOpen. https://doi.org/10.5772/intechopen.85533

**Rai, P.K., Rai, A., Sharma, N.K., Singh, T. & Kumar, Y.** 2023. Limitations of biofertilizers and their revitalization through nanotechnology. *Journal of Cleaner Production*, 418, 138194. https://doi.org/10.1016/j.jclepro.2023.138194

**Ramírez, A.** 2013. *Innovative uses of fisheries by-products.* GLOBEFISH Research Programme. Vol. 110. Rome, FAO. https://openknowledge.fao.org/server/api/core/bitstreams/10877502-1bdc-4a27-8229-a90c91d09c79/content

**Ramírez, A.D., Humphries, A.C., Woodgate, S. & Wilkinson, R.** 2012. Greenhouse gas life cycle assessment of products arising from the rendering of mammalian byproducts in the UK. *Environmental Science and Technology*, 46(1): 447–453. https://doi.org/10.1021/es201983t

**Ramos-Hernández, R., Sánchez-Ramírez, C., Jiménez-Nieto, Y.A., Rodríguez-Parada, A., Mancilla-Gómez, M. & Nuñez-Dorantes, J.C.** 2021. Dynamic evaluation of livestock feed supply chain from the use of ethanol vinasses. In: J.A. Zapata-Cortes, G. Alor-Hernández, C. Sánchez-Ramírez & J.L. García-Alcaraz, eds. *New perspectives on enterprise decision-making applying artificial intelligence techniques*, pp. 309–334. London, Springer Nature. https://doi.org/10.1007/978-3-030-71115-3_14

**Rao, M., Bast, A. & De Boer, A.** 2021. Valorized food processing by-products in the EU: Finding the balance between safety, nutrition, and sustainability. *Sustainability*, 13(8): 4428. https://doi.org/10.3390/su13084428

**Ratnasari, A., Syafiuddin, A., Mehmood, M.A. & Boopathy, R.** 2023. A review of the vermicomposting process of organic and inorganic waste in soils: Additives effects, bioconversion process, and recommendations. *Bioresource Technology Reports*, 21, 101332. https://doi.org/10.1016/j.biteb.2023.101332

**Raza, Q.U.A., Bashir, M.A., Rehim, A., Sial, M.U., Raza, H.M.A., Atif, H.M., Brito, A.F. & Geng, Y.** 2021. Sugarcane industrial byproducts as challenges to environmental safety and their remedies: A review. *Water*, 13(24): 3495. https://doi.org/10.3390/w13243495

**Reichel, A., De Schoenmakere, M. & Gillabel, J.** 2016. *Circular economy in Europe: Developing the knowledge base*. European Environment Agency report No. 2. Luxembourg, Publications Office of the European Union. [Cited 19 July 2023]. https://www.eea.europa.eu/en/analysis/publications/circular-economy-in-europe

**Reilly, M. & Willenbockel, D.** 2010. Managing uncertainty: A review of food system scenario analysis and modelling. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 365(1554): 3049–3063. https://doi.org/10.1098/rstb.2010.0141

**Rendertech. 2019.** *Low temperature rendering for competitive advantage*. White paper. Auckland, New Zealand, Rendertech. https://www.rendertech.co.nz/media/website_pages/blog/white-paper-low-temperature-rendering-for-competitive-advantage/Rendertech-WhitePaper-LowTemperatureRendering-V4-September-2019-web.pdf

**Riaz, T., Iqbal, M.W., Mahmood, S., Yasmin, I., Leghari, A.A., Rehman, A., Mushtaq, A., Ali, K., Azam, M. & Bilal, M.** 2023. Cottonseed oil: A review of extraction techniques, physicochemical, functional, and nutritional properties. *Critical Reviews in Food Science and Nutrition*, 63(9): 1219–1237. https://doi.org/10.1080/10408398.2021.1963206

**Rich, K.M., Schaefer, K.A., Thapa, B., Hagerman, A.D. & Shear, H.E.** 2022. An overview of meat processing in Africa. In: C. Jenane, J.M. Ulimwengu & G. Tadesse, eds. *Annual trends and outlook report: Agrifood processing strategies for successful food systems transformation in Africa*, pp. 33–43. Washington, DC., IFPRI (International Food Policy Research Institute). https://hdl.handle.net/10568/141055

**Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S.E., Donges, J.F., Drüke, M., Fetzer, I., Bala, G., Von Bloh, W. & Feulner, G.** 2023. Earth beyond six of nine planetary boundaries. *Science Advances*, 9(37): eadh2458. https://doi.org/10.1126/sciadv.adh2458

**Rockström, J., Gupta, J., Qin, D., Lade, S.J., Abrams, J.F., Andersen, L.S., Armstrong McKay, D.I., Bai, X., Bala, G., Bunn, S.E. & Ciobanu, D.** 2023. Safe and just Earth system boundaries. *Nature,* 619, 102–111. https://doi.org/10.1038/s41586-023-06083-8

**Rodrigues Reis, C.E. & Hu, B.** 2017. Vinasse from sugarcane ethanol production: Better treatment or better utilization? *Frontiers Energy Research*, 5(7). https://doi.org/10.3389/fenrg.2017.00007

**Rodríguez, L. & Preston, T.R.** 1997. Local feed resources and indigenous breeds: Fundamental issues in integrated farming systems. *Livestock Research for Rural Development*, 9(2): 9–18. [Cited 30 June 2025]. http://www.lrrd.org/lrrd9/2/lylian92.htm

**Röös, E., Sundberg, C. & Hansson, P.-A.** 2010. Uncertainties in the carbon footprint of food products: A case study on table potatoes. *The International Journal of Life Cycle Assessment*, 15(5): 478–488. https://doi.org/10.1007/s11367-010-0171-8

**Rossi, W. & Davis, A.** 2014. Meat and bone meal as an alternative to fish meal and soybean meal-based diets for Florida Pompano, *Trachinotis carolinus* L. *Journal of the World Aquaculture Society*, 45(6): 613–624. https://doi.org/10.1111/jwas.12155

**Rufino, M.C., Rowe, E.C., Delve, R.J. & Giller, K.E.** 2006. Nitrogen cycling efficiencies through resource-poor African crop–livestock systems. *Agriculture, Ecosystems & Environment*, 112(4): 261–282. https://doi.org/10.1016/j.agee.2005.08.028

**Ruiz, M. de los A., Adema, E.O., Rucci, T. & Babinec, F.J.** 2004. *Produccion y calidad de forraje de gramineas perennes en diferentes ambientes del caldenal.* 35 pp. Buenos Aires, INTA (Insituto Nacional de Tecnología Agropecuaria. https://www.produccion-animal.com.ar/produccion_y_manejo_pasturas/pasturas%20artificiales/31-gramineas_perennes_en_caldenal.pdf

**RIRDC (Rural Industries Research and Development Corporation).** 2015. *Grower options for spent litter utilisation*. Publication No. 14/093. Wagga Wagga, Australia, RIRDC. https://agrifutures.com.au/wp-content/uploads/publications/14-093.pdf

**Rutherfurd, S.M. & Moughan, P.J.** 2012. Available versus digestible dietary amino acids. *British Journal of Nutrition*, 108(2): S298-S305. https://doi.org/10.1017/s0007114512002528

**Sakita, G. Zanuto, Lima, P. de Mello Tavares, Abdalla Filho, A.L., Bompadre, T.F. Ventosso, Ovani, V.S., Chaves, C. de Miranda e Silva, Bizzuti, B.E., Costa, W. dos Santos, da, Paim, T. do Prado, Campioni, T. Sila, Oliva Neto, P., Louvandini, H. & Abdalla, A.L.** 2022. Treating tropical grass with fibrolytic enzymes from the fungus *Trichoderma reesei*: Effects on animal performance, digestibility and enteric methane emissions of growing lambs. *Animal Feed Science and Technology*, 286, 115253. https://doi.org/10.1016/j.anifeedsci.2022.115253

**Salami, S.A., Luciano, G., O'Grady, M.N., Biondi, L., Newbold, C.J., Kerry, J.P. & Priolo, A.** 2019. Sustainability of feeding plant by-products: A review of the implications for ruminant meat production. *Animal Feed Science and Technology*, 251, 37–55. https://doi.org/10.1016/J.ANIFEEDSCI.2019.02.006

**Sanchez, M. & Preston, T.R.** 1980. Sugarcane juice as cattle feed: Comparisons with molasses in the presence or absence of protein supplement. *Tropical Animal Health and Production*, 5(2): 117–124. https://www.cipav.org.co/TAP/TAP/TAP52/5_2_3.pdf

**Sandström, V., Chrysafi, A., Lamminen, M., Troell, M., Jalava, M., Piipponen, J., Siebert, S., Van Hal, O., Virkki, V. & Kummu, M.** 2022. Food system by-products upcycled in livestock and aquaculture feeds can increase global food supply. *Nature Food*, 3, 729–740. https://doi.org/10.1038/s43016-022-00589-6

**Sar, T., Harirchi, S., Ramezani, M., Bulkan, G., Akbas, M.Y., Pandey, A. & Taherzadeh, M.J.** 2022. Potential utilization of dairy industries by-products and wastes through microbial processes: A review. *Science of the Total Environment*, 810, 152253. https://doi.org/10.1016/j.scitotenv.2021.152253

**Sarnklong, C., Cone, J. W., Pellikaan, W., & Hendriks, W. H.** 2010. Utilization of rice straw and different treatments to improve its feed value for ruminants: A review. *Asian-Australasian Journal of Animal Sciences*, 23(5): 680–692. https://doi.org/10.5713/ajas.2010.80619

**Satter, L.D., Klopfenstein, T., Erickson, G.E. & Powell, J.** 2005. Phosphorus and dairy/beef nutrition. *American Society of Agronomy, Crop Science Society of America, Soil Science Society of America*, p. 677. [cited 17 September 2025]. https://digitalcommons.unl.edu/animalscifacpub/549

**Sauvant, D., Perez, J.-M. & Tran, G.** 2002. *Tables de composition et de valeur nutritive des matières premières destinées aux animaux d'élevage: Porcs, volailles, bovins, ovins, caprins, lapins, chevaux, poissons*. 304 pp. Paris, INRA–CIRAD–AFZ. https://www.quae.com/produit/592/9782738011589/tables-de-composition-et-de-valeur-nutritive-des-matieres-premieres-destinees-aux-animaux-d-elevage?affiliate_code=

**Scarborough, P., Clark, M., Cobiac, L., Papier, K., Knuppel, A., Lynch, J., Harrington, R., Key, T. & Springmann, M.** 2023. Vegans, vegetarians, fish-eaters and meat-eaters in the UK show discrepant environmental impacts. *Nature Food*, 4(7): 565–574. https://doi.org/10.1038/s43016-023-00795-w

**Scarlat, N., Fahl, F., Dallemand, J.F., Monforti, F. & Motola, V.** 2018. A spatial analysis of biogas potential from manure in Europe. *Renewable and Sustainable Energy Reviews*, 94, 915–930. https://doi.org/10.1016/j.rser.2018.06.035

**Schindler, S., Wittig, M., Zelena, K., Krings, U., Bez, J., Eisner, P. & Berger, R.G.** 2011. Lactic fermentation to improve the aroma of protein extracts of sweet lupin (*Lupinus angustifolius*), *Food Chemistry*, 128(2): 330–337. https://doi.org/10.1016/j.foodchem.2011.03.024

**Schlegel, K., Leidigkeit, A., Eisner, P. & Schweiggert-Weisz, U.** 2019. Technofunctional and sensory properties of fermented lupin protein isolates. *Foods*, 8(12): 678. https://doi.org/10.3390/foods8120678

**Schmidt, J. & De Rosa, M.** 2020. *Life Cycle Assessment of palm oil at United Plantations Berhad 2020, Results for 2004–2019. Summary report.* Teluk Intan, Malaysia, United Plantations Berhad. https://lca-net.com/files/Report-summary-2020_20200707.pdf

**Schreefel, L., Creamer, R.E., Van Zanten, H.H.E., De Olde, E.M. & Schrijver, P.** 2023. How to monitor the `success' of (regenerative) agriculture: A perspective. *Global Food Security*, 43, 100810. https://doi.org/10.1016/j.gfs.2024.100810

**Sefeedpari, P., Vellinga, T., Rafiee, S., Sharifi, M., Shine, P. & Pishgar-Komleh, S.H.** 2019. Technical, environmental and cost-benefit assessment of manure management chain: A case study of large scale dairy farming. *Journal of Cleaner Production*, 233, 857–868. https://doi.org/10.1016/j.jclepro.2019.06.146

**Sengupta, A. & Behra, J.** 2014. Comprehensive view of the chemistry, manufacturing & applications of lanolin extracted from wool pretreatment. *American Journal of Engineering Research*, 3(7): 33–43. https://www.ajer.org/papers/v3(7)/F0373343.pdf

**Sepperer, T., Tondi, G., Petutschnigg, A., Young, T.M. & Steiner, K.** 2020. Mitigation of ammonia emissions from cattle manure slurry by tannins and tannin-based polymers. *Biomolecules*, 10(4): 581. https://doi.org/10.3390/biom10040581

**Serra, V., Salvatori, G. & Pastorelli, G.** 2021. Dietary polyphenol supplementation in food producing animals: Effects on the quality of derived products. *Animals*, 11(2): 401. https://doi.org/10.3390/ani11020401

**Shan, G., Li, W., Gao, Y., Tan, W. & Xi, B.** 2021. Additives for reducing nitrogen loss during composting: A review. *Journal of Cleaner Production*, 307, 127308. https://doi.org/10.1016/j.jclepro.2021.127308

**Sharma, S., Imran, Z., Mitra, A., Verma, M. & Joshi, S.** 2021. A brief review on the utilization of waste products from the meat industry. *International Journal of Research and Analytical Reviews*, 8(4): 856–863. https://www.researchgate.net/profile/Abhirup-Mitra-2/publication/356429891_A_brief_review_on_the_utilization_of_waste_products_from_the_meat_industry/links/619b74d561f0987720c2dbeb/A-brief-review-on-the-utilization-of-waste-products-from-the-meat-industry.pdf

**Shelke, S.K., Chhabra, A., Puniya, A.K. & Sehgal, J.P.** 2009. In vitro degradation of sugarcane bagasse based ruminant rations using anaerobic fungi. *Annals of Microbiology*, 59(3): 415–418. https://doi.org/10.1007/BF03175124

**Shelton, J.L., Hemann, M.D., Strode, R.M., Brashear, G.L., Ellis, M., McKeith, F.K., Bidner, T.D. & Southern, L.L.** 2001. Effect of different protein sources on growth and carcass traits in growing-finishing pigs. *Journal of Animal Science*, 79(9): 2428–2435. https://doi.org/10.2527/2001.7992428x

**Shen, Y., Abeynayake, R., Sun, X., Ran, T., Li, J., Chen, L. & Yang, W.** 2019. Feed nutritional value of brewers' spent grain residue resulting from protease aided protein removal. *Journal of Animal Science and Biotechnology*, 10, 78. https://doi.org/10.1186/s40104-019-0382-1

**Shi, J., Puig, R., Sang, J. & Lin, W.** 2016. A comprehensive evaluation of physical and environmental performances for wet-white leather manufacture. *Journal of Cleaner Production*, 139, 1512–1519. https://doi.org/10.1016/j.jclepro.2016.08.120

**Shingfield, K.J., Lee, M.R.F., Humphries, D.J., Scollan, N.D., Toivonen, V., Beever, D.E. & Reynolds, C.K.** 2011. Effect of linseed oil and fish oil alone or as an equal mixture on ruminal fatty acid metabolism in growing steers fed maize silage-based diets. *Journal of Animal Science*, 89(11): 3728–3741. https://doi.org/10.2527/jas.2011-4047

**Shurson, G.C.** 2020. "What a waste" – Can we improve sustainability of food animal production systems by recycling food waste streams into animal feed in an era of health, climate, and economic crises? *Sustainability*, 12(17): 7071. https://doi.org/10.3390/su12177071

**Siewe, F.B., Akouan Ekorong, F.A., Karkal, S.S., Cathrine, M.S.B. & Kudre, T.G.** 2019. Green and innovative techniques for recovery of valuable compounds from seafood by-products and discards: A review. *Trends in Food Science & Technology,* 85, 10–22. https://doi.org/10.1016/j.tifs.2018.12.004

**Singh, A., Christensen, T. & Panoutsou, C.** 2021. Policy review for biomass value chains in the European bioeconomy. *Global Transitions*, 3, 13–42. https://doi.org/10.1016/j.glt.2020.11.003

**Singh, J.A., Noorbaloochi, S., MacDonald, R. & Maxwell, L.J.** 2015. Chondroitin for osteoarthrosis. *Cochrane Database of Systematic Reviews*, 1(1): CD005614. https://doi.org/10.1002/14651858.CD005614.pub2

**Smetana, S., Schmitt, E. & Mathys, A.** 2019. Sustainable use of *Hermetia illucens* insect biomass for feed and food: Attributional and consequential life cycle assessment. *Resources, Conservation and Recycling*, 144, 285–296. https://doi.org/10.1016/j.resconrec.2019.01.042

**Smith, K., Watson, A.W., Lonnie, M., Peeters, W.M., Oonincx, D., Tsoutsoura, N., Simon-Miquel, G., Szepe, K., Cochetel, N., Pearson, A.G., Witard, O.C., Salter, A.M., Bennett, M. & Corfe, B.M.** 2024. Meeting the global protein supply requirements of a growing and ageing population. *European Journal of Nutrition*, 63(5): 1425–1433. https://doi.org/10.1007/s00394-024-03358-2

**Smits, M.C.J., Valk, H., Elzing, A. & Keen, A.** 1995. Effect of protein nutrition on ammonia emission from a cubicle house for dairy cattle. *Livestock Production Science*, 44(2): 147–156. https://doi.org/10.1016/0301-6226(95)00068-6

**Socas-Rodríguez, B., Álvarez-Rivera, G., Valdés, A., Ibáñez, E. & Cifuentes, A.** 2021. Food by-products and food wastes: Are they safe enough for their valorization? *Trends in Food Science & Technology*, 114, 133–147. https://doi.org/10.1016/j.tifs.2021.05.002

**Solà-Oriol, D., Roura, E. & Torrallardona, D.** 2011. Feed preference in pigs: Effect of selected protein, fat, and fiber sources at different inclusion rates. *Journal of Animal Science*, 89(10): 3219–3227. https://doi.org/10.2527/jas.2011-3885

**Somda, J., Nianogo, A.J., Nassa, S. & Sanou, S.** 2002. Soil fertility management and socio-economic factors in crop-livestock systems in Burkina Faso: A case study of composting technology. *Ecological Economics*, 43(2–3): 175–183. https://doi.org/10.1016/S0921-8009(02)00208-2

**Soussana, J.F. & Lemaire, G.** 2014. Coupling carbon and nitrogen cycles for environmentally sustainable intensification of grasslands and crop-livestock systems. *Agriculture, Ecoxystems & Environment*, 190, 9–17. https://doi.org/10.1016/j.agee.2013.10.012

**Spek, J.-W. & Blok, M.-C., eds.** 2018. *CVB feed table 2018: Chemical composition and nutritive values of feedstuffs*. The Hague, Kingdom of the Netherlands, FND (Federatie Nederlandse Diervoederketen – Dutch Feed Chain Federation). https://appec-h.com/wp-content/uploads/2024/08/CVB-Feed-Table-2018_Chemical-composition-and-nutritional-values-of-feedstuffs.pdf

**Srivastava, S.** 2020. Diversification of sugar and sugarcane industry: Agro-industrial alternatives. In: N. Mohan & P. Singh, eds. *Sugar and Sugar Derivatives: Changing Consumer Preferences*, pp. 151–169. Singapore, Springer. https://doi.org/10.1007/978-981-15-6663-9_10

**STATISTA.** 2023. Energy generated from biogas in China from 2010 to 2021. In: *STATISTA*. [Cited 30 June 2025]. https://www.statista.com/statistics/963294/china-energy-production-from-biogas/

**Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., De Vries, W., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B. & Sörlin, S.** 2015. Planetary boundaries: Guiding human development on a changing planet. *Science*, 347, 1259855. https://doi.org/10.1126/science.1259855

**Steffen, W. & Stafford Smith, M.** 2013. Planetary boundaries, equity and global sustainability: Why wealthy countries could benefit from more equity. *Current Opinion in Environmental Sustainability*, 5(3–4): 403–408. https://doi.org/10.1016/j.cosust.2013.04.007

**Stegmann, P., Londo, M. & Junginger, M.** 2020. The circular bioeconomy: Its elements and role in Europe, bioeconomy clusters. *Resources, Conservation & Recycling: X*, 6, 100029. https://doi.org/10.1016/j.rcrx.2019.100029

**Struhs, E., Mirkouei, A., You, Y. & Mohajeri, A.** 2020. Techno-economic and environmental assessments for nutrient-rich biochar production from cattle manure: A case study in Idaho, USA. *Applied Energy*, 279, 115782. https://doi.org/10.1016/j.apenergy.2020.115782

**Sukumaran, R.K., Singhania, R.R. & Pandey, A.** 2005. Microbial cellulases – Production, applications and challenges. *Journal of Scientific & Industrial Research*, 64(11): 832–844. https://nopr.niscpr.res.in/bitstream/123456789/5375/1/JSIR%2064%2811%29%20832-844.pdf

**Sureshkumar, S., Song, J., Sampath, V. & Kim, I.** 2023. Exogenous enzymes as zootechnical additives in monogastric animal feed: A review. *Agriculture*, 13(12): 2195. https://doi.org/10.3390/agriculture13122195

**Suri, S., Singh, A., Nema, P.K., Malakar, S. & Arora, V.K.** 2022. Sweet lime (*Citrus limetta*) peel waste drying approaches and effect on quality attributes, phytochemical and functional properties. *Food Bioscience*, 48, 101789. https://doi.org/10.1016/j.fbio.2022.101789

**Sutton, M.A., Howard, C.M., Mason, K.E., Brownlie, W.J. & Cordovil, C. Marques dos Santos, eds.** 2022. *Nitrogen opportunities for agriculture, food & environment. UNECE guidance document on integrated sustainable nitrogen management*. 166 pp. Edinburgh, UK, UK Centre for Ecology & Hydrology (UKCEH). https://unece.org/sites/default/files/2022-11/UNECE_NitroOpps%20red.pdf

**Sutton, M.A., Mason, K.E., Bleeker, A., Hicks, W.K., Masso, C., Raghuram, N., Reis, S. & Bekunda, M.** 2020. Just enough nitrogen: Summary and synthesis of outcomes. In: M.A. Sutton, K.E. Mason, A. Bleeker, W.K. Hicks, C. Masso, N. Raghuram, S. Reis & M. Bekunda, eds. *Just enough nitrogen: perspectives on how to get there for regions with too much and too little nitrogen,* pp. 1–25. Cham, Switzerland, Springer International Publishing. https://doi.org/10.1007/978-3-030-58065-0_1

**Swensson, C.** 2003. Relationship between content of crude protein in rations for dairy cows, N in urine and ammonia release. *Livestock Production Science*, 84(2): 1829–1838. https://doi.org/10.3168/jds.S0022-0302(02)74257-4

**Tan, M., Hou, Y., Zhang, L., Shi, S., Long, W., Ma, Y., Zhang, T., Li, F. & Oenema, O.** 2021. Operational costs and neglect of end-users are the main barriers to improving manure treatment in intensive livestock farms. *Journal of Cleaner Production*, 289, 125149. https://doi.org/10.1016/j.jclepro.2020.125149

**Tanksley, T.D.** 1990. Cottonseed meal. In: P.A. Thacker & R.N. Kirkwood, eds. *Non-traditional feed sources for use in swine production*, pp. 139–151. Boca Raton, USA, CRC Press. https://doi.org/10.1201/9780203711248

**Tedeschi, L.O., Muir, J.P., Riley, D.G. & Fox, D.G.** 2015. The role of ruminant animals in sustainable livestock intensification programs. *International Journal of Sustainable Development & World Ecology*, 22(5): 452-465. https://doi.org/10.1080/13504509.2015.1075441

**Teferi, S.C.** 2020. A review on food hygiene knowledge, practice and food safety in Ethiopia. *Scientific Journal of Food Science and Nutrition*, 105, 24–31. http://dx.doi.org/10.7176/FSQM/105-04

**Tesfaye, T., Sithole, B., Ramjugernath, D. & Chunilall, V.** 2017. Valorisation of chicken feathers: Characterisation of chemical properties. *Waste Management*, 68, 626–635. https://doi.org/10.1016/j.wasman.2017.06.050

**Tetra Pak.** 2023. Whey processing. *Dairy processing handbook*. Tetra Pak. https://dairyprocessinghandbook.tetrapak.com/chapter/milk-and-whey-fractionation

**Toldra, F., Aristoy, M.-C., Mora, L. & Reig, M.** 2012. Innovations in value-addition of edible meat by-products. *Meat Science*, 92(3): 290–296. https://doi.org/10.1016/j.meatsci.2012.04.004

**Tsapekos, P., Kougias, P.G., Treu, L., Campanaro, S. & Angelidaki, I.** 2017. Process performance and comparative metagenomic analysis during co-digestion of manure and lignocellulosic biomass for biogas production. *Applied Energy*, 185(part 1): 126–135. https://doi.org/10.1016/j.apenergy.2016.10.081

**Tufa, A.H., Alene, A.D., Cole, S.M., Manda, J., Feleke, S., Abdoulaye, T., Chikoye, D. & Manyong, V.** 2022. Gender differences in technology adoption and agricultural productivity: Evidence from Malawi. *World Development*, 159, 106027. https://doi.org/10.1016/j.worlddev.2022.106027

**Tzachor, A., Richards, C.E. & Holt, L.** 2021. Future foods for risk-resilient diets. *Nature Food*, 2, 326–329. https://doi.org/10.1038/s43016-021-00269-x

**Tzamaloukas, O., Neofytou, M.C. & Simitzis, P.E.** 2021. Application of olive by-products in livestock with emphasis on small ruminants: Implications on rumen function, growth performance, milk and meat quality. *Animals*, 11(2): 531. https://doi.org/10.3390/ani11020531

**Uddin, M.N., Siddiki, S.Y.A., Mofijur, M., Djavanroodi, F., Hazrat, M.A., Show, P.L., Ahmed, S.F., & Chu, Y.** 2021. Prospects of bioenergy production from organic waste using anaerobic digestion technology: A mini review. *Frontiers in Energy Research: Bioenergy and Biofuels*, 9, 627093. https://doi.org/10.3389/fenrg.2021.627093

**Udemezue, J. & Mmeremikwu, L. 2021.** Bio-fertilizer and constraints to adoption of biofertilizer among the users. *Advances in Agricultural Technology & Plant Sciences*, 4(1): 1–7. https://academicstrive.com/AATPS/AATPS180057.pdf

**UN (United Nations).** 2022. *World population prospects 2022: Summary of results*. In: *United Nations*. New York, USA. [Cited 30 June 2025]. https://www.un.org/development/desa/pd/content/World-Population-Prospects-2022

**UN & ADB (Asian Development Bank).** 2016. *Intraregional trade in leather and leather products in South Asia: Identification of potential regional supply chains*. Manila, ADB and Geneva, Switzerland, UNCTAD (United Nations Trade and Development). https://www.adb.org/sites/default/files/publication/399271/intraregional-trade-leather-south-asia.pdf

**UNDP (United Nations Development Programme).** 2024. Paraguay: Sustainable soy and beef. In: *UNDP*. New York, USA. [Cited 30 June 2025]. https://www.undp.org/facs/paraguay-sustainable-soy-and-beef

**UNEP (United Nations Environment Programme).** 2024. *Global bioeconomy assessment: Coordinated efforts of policy, innovation, and sustainability for a greener future*. Nairobi, UNEP. https://doi.org/10.59117/20.500.11822/45332

**USDA (United States Department of Agriculture).** 2016. Production, Supply and Distribution Online (PS&D). [Accessed on 30 June 2025]. In: *Foreign Agricultural Service*. Washington, DC., USDA. Available at https://apps.fas.usda.gov/psdonline/app/index.html#/app/home

**USDA.** 2023. Keeping U.S. agriculture healthy for America and the World – 2022 impact report. In: *APHIS (Animal and Plant Health Inspection Service)*. Washington, DC., USDA. https://www.aphis.usda.gov/sites/default/files/2022-impact-report.pdf

**USDA.** 2024. Production – Beef. [Accessed on 30 June 2025]. In: *Foreign Agricultural Service*. Washington, DC., USDA. Available at https://www.fas.usda.gov/data/production/commodity/0111000

**USDA & APHIS (Animal and Plant Health Inspection Service).** 2023. Blood products (other than those originating from birds) for technical purposes. https://www.aphis.usda.gov/sites/default/files/ja-pbp-tech.pdf

**Vadas, P.A., Good, L.W., Jokela, W.E., Karthikeyan, K.G., Arriaga, F.J. & Stock, M.** 2017. Quantifying the impact of seasonal and short-term manure application decisions on phosphorus loss in surface runoff. *Journal of Environmental Quality*, 46(6): 1395–1402. https://doi.org/10.2134/jeq2016.06.0220

**Vaishnav, S., Saini, T., Chauhan, A., Gaur, G.K., Tiwari, R., Dutt, T. & Tarafdar, A.** 2023. Livestock and poultry farm wastewater treatment and its valorization for generating value-added products: Recent updates and way forward. *Bioresource Technology*, 382, 129170. https://doi.org/10.1016/j.biortech.2023.129170

**Valls-Val, K., Ibáñez-Forés, V. & Bovea, M.D.** 2023. Tools for assessing qualitatively the level of circularity of organisations: Applicability to different sectors. *Sustainable Production and Consumption*, 36, 513–525. https://doi.org/10.1016/j.spc.2023.01.023

**Van der Stelt, B., Temminghoff, E.J.M., Van Vliet, P.C.J. & Van Riemsdijk, W.H.** 2007. Volatilization of ammonia from manure as affected by manure additives, temperature and mixing. *Bioresource Technology*, 98(18): 3449–3455. https://doi.org/10.1016/j.biortech.2006.11.004

**Van Donselaar, E.** 2015. Liquid feeding: Don't let microorganisms control your profit. In: *Proceedings of the 2015 London Swine Conference: Production Technologies to Meet Market Demands*, *1–2 April 2015*, pp. 135–137. Wallingford, UK, CABI. [Cited 30 June 2025]. https://www.cabidigitallibrary.org/doi/pdf/10.5555/20153400466

**Van Hal, O., De Boer, I.J.M., Muller, A., De Vries, S., Erb, K.H., Schader, C., Gerrits, W.J.J. & Van Zanten, H.H.E.** 2019. Upcycling food leftovers and grass resources through livestock: Impact of livestock system and productivity. *Journal of Cleaner Production*, 219, 485–496. https://doi.org/10.1016/j.jclepro.2019.01.329

**Van Hal, O., Weijenberg, A.A.A., De Boer, I.J.M. & Van Zanten, H.H.E.** 2019. Accounting for feed-food competition in environmental impact assessment: Towards a resource efficient food-system. *Journal of Cleaner Production*, 240, 118241. https://doi.org/10.1016/j.jclepro.2019.118241

**Van Loon, M.P., Vonk, W.J., Hijbeek, R., Van Ittersum, M.K. & Ten Berge, H.F.M.** 2023. Circularity indicators and their relation with nutrient use efficiency in agriculture and food systems. *Agricultural Systems*, 207, 103610. https://doi.org/10.1016/j.agsy.2023.103610

**Van Raamsdonk, L.W.D., Meijer, N., Gerrits, E.W.J. & Appel, M.J.** 2023. New approaches for safe use of food by-products and biowaste in the feed production chain. *Journal of Cleaner Production*, 388, 135954. https://doi.org/10.1016/j.jclepro.2023.135954

**Van Zanten, H.H.E., Herrero, M., Van Hal, O., Röös, E., Muller, A., Garnett, T., Gerber, P.J., Schader, C. & De Boer, I.J.M**. 2018. Defining a land boundary for sustainable livestock consumption. *Global Change Biology*, 24(9): 4185–4194. https://doi.org/10.1111/gcb.14321

**Van Zanten, H.H.E., Meerburg, B.G., Bikker, P., Herrero, M. & De Boer, I.J.M.** 2016a. Opinion paper: The role of livestock in a sustainable diet: A land-use perspective. *Animal*, 10(4): 547–549. https://doi.org/10.1017/s1751731115002694

**Van Zanten, H.H.E., Mollenhorst, H., De Vries, J.W., Van Middelaar, C.E., Van Kernebeek, H.R. J. & De Boer, I.J.M.** 2013. Assessing environmental consequences of using co-products in animal feed. *The International Journal of Life Cycle Assessment*, 19, 79–88. https://doi.org/10.1007/s11367-013-0633-x

**Van Zanten, H.H.E., Mollenhorst, H., Klootwijk, C.W., Van Middelaar, C.E. & De Boer, I.J.M.** 2016b. Global food supply: Land use efficiency of livestock systems. *The International Journal of Life Cycle Assessment*, 21, 747–758. https://doi.org/10.1007/s11367-015-0944-1

**Van Zanten, H.H.E., Oonincx, D.G.A.B., Mollenhorst, H., Bikker, P., Meerburg, B.G. & De Boer, I.J.M.** 2014. Can environmental impact of livestock feed be reduced by using waste-fed housefly larvae? In: Schenck, R. & Huizenga, D., eds. *Proceedings of the 9th International Life Cycle Assessment of Foods Conference in the Agri-Food Sector (LCA Food 2014)*, 1455–1461. Vashon, USA, ACLCA. https://www.cabidigitallibrary.org/doi/pdf/10.5555/20153264605

**Van Zanten, H.H.E., Simon, W., Van Selm, B., Wacker, J., Maindi, T.I., Frehner, A., Hijbeek, I., Van Ittersum, M.K. & Herrero, M.** 2023. Circularity in Europe strengthens the sustainability of the global food system. *Nature Food*, 4, 320–330. https://doi.org/10.1038/s43016-023-00734-9

**Van Zanten, H.H.E., Van Ittersum, M.K. & De Boer, I.J.M.** 2019. The role of farm animals in a circular food system. *Global Food Security*, 21, 18–22. https://doi.org/10.1016/j.gfs.2019.06.003

**VanderZaag, A.C., Glenn, A. & Baldé, H.** 2022. Manure methane emissions over three years at a swine farm in western Canada. *Journal of Environmental Quality*, 51(3): 301–311. https://doi.org/10.1002/jeq2.20336

**Varijakshapanicker, P., Mckune, S., Miller, L., Hendrickx, S., Balehegn, M., Dahl, G.E. & Adesogan, A.T.** 2019. Sustainable livestock systems to improve human health, nutrition, and economic status. *Animal Frontiers*, 9(4): 39–50. https://doi.org/10.1093/af/vfz041

**Vastolo, A., Calabrò, S. & Cutrignelli, M.I.** 2022. A review on the use of agro-industrial CO-products in animals' diets. *Italian Journal of Animal Science*, 21(1): 577–594. https://doi.org/10.1080/1828051X.2022.2039562

**Veerabrahmam, K. & Prasad, D.S.** 2021. A review of eggshell powder on engineering properties of expansive soil. *Indian Journal of Science and Technology*, 14(5): 415–426. https://doi.org/10.17485/IJST/v14i5.56

**Venugopal, V.** 2022. Green processing of seafood waste biomass towards blue economy. *Current Research in Environmental Sustainability*, 4, 100164. http://dx.doi.org/10.1016/j.crsust.2022.100164

**Vidaurre-Arbizu, M., Pérez-Bou, S., Zuazua-Ros, A. & Martín-Gómez, C.** 2021. From the leather industry to building sector: Exploration of potential applications of discarded solid wastes. *Journal of Cleaner Production*, 291, 125960. https://doi.org/10.1016/j.jclepro.2021.125960

**Vlachou, M., Pexara, A., Solomakos, N. & Govaris, A.** 2022. Ochratoxin A in slaughtered pigs and pork products. *Toxins*, 14(2): 67. https://doi.org/10.3390/toxins14020067

**Voinitchi, C., Gaidau, C., Capatana Tudorie, F., Niculescu, M., Stanca, M. & Alexe, C.A.** 2022. Collagen and keratin hydrolysates to delay the setting of gypsum plaster. *Materials*, 15(24): 8817. https://doi.org/10.3390/ma15248817

**Voogt, W., De Visser, P.H.E., Van Winkel, A., Cuijpers, W.J.M. & Van de Burgt, G.J.H.M.** 2010. Nutrient management in organic greenhouse production: Navigation between constraints. *ISHS [International Society for Horticultural Science] Acta* Horticulture, 915, 75–82. https://doi.org/10.17660/ActaHortic.2011.915.9

**Walkowiak, S., Taylor, D., Fu, B.X., Drul, D., Pleskach, K. & Tittlemier, S.A.** 2022. Ergot in Canadian cereals – relevance, occurrence, and current status. *Canadian Journal of Plant Pathology*, 44(6): 793–805. https://doi.org/10.1080/07060661.2022.2077451

**Wani, A.D., Prasad, W., Khamrui, K. & Jamb, S.** 2022. A review on quality attributes and utilization of ghee residue, an under-utilized dairy by-product. *Future Foods*, 5, 100131. https://doi.org/10.1016/j.fufo.2022.100131

**Watson, J., Wang, T., Si, B., Chen, W., Aierzhati, A. & Zhang, Y.** 2020. Valorization of hydrothermal liquefaction aqueous phase: Pathways towards commercial viability. *Progress in Energy and Combustion Science*, 77, 100819. http://dx.doi.org/10.1016/j.pecs.2019.100819

**Watson, J., Zhang, Y., Si, B., Chen, W., & de Souza, R.** 2018. Gasification of biowaste: A critical review and outlooks. *Renewable and Sustainable Energy Reviews*, 83(suppl. C): 1–17. https://doi.org/10.1016/j.rser.2017.10.003

**WBCSD (World Business Council for Sustainable Development).** 2019. CEO guide to the circular bioeconomy. In: *WBCSD*. Geneva, Switzerland. [Cited 30 June 2025]. https://www.wbcsd.org/resources/ceo-guide-to-the-circular-bioeconomy/

**Webb, J., Menzi, H., Pain, B.F., Misselbrook, T.H., Dämmgen, U., Hendriks, H. & Döhler, H.** 2005. Managing ammonia emissions from livestock production in Europe. *Environmental Pollution*, 135(3): 399–406. https://doi.org/10.1016/j.envpol.2004.11.013

**Wei, S., Zhu, Z., Zhao, J., Chadwick, D.R. & Dong, H.** 2021. Policies and regulations for promoting manure management for sustainable livestock production in China: A review. *Frontiers of Agricultural Science and Engineering*, 8(1): 45–57. http://dx.doi.org/10.15302/J-FASE-2020369

**Weide, N.** 2004. The use of gelatin hydrolyzate in clinical orthopedic healthy dogs and dogs with chronic musculoskeletal disorder. Hanover, Germany, University of Veterinary Medicine Hannover. PhD dissertation.

**Weidema, B.P. Ekvall, T. & Heijungs, R.** 2009. Guidelines for application of deepened and broadened Life Cycle Assessment (LCA). CALCAS Project No. 037075. Leiden, Kingdom of the Netherlands, Leiden University. https://web.universiteitleiden.nl/cml/ssp/publications/calcas_report_d18.pdf

**White, P. J. & Brown, P.** 2010. Plant nutrition for sustainable development and global health. *Annals of Botany*, 105(7): 1073–1080. https://doi.org/10.1093/aob/mcq085

**WHO (World Health Organization), FAO, WOAH (World Organisation for Animal Health) & UNEP.** 2022. *One Health Joint Plan of Action (2022–2026): Working together for the health of humans, animals, plants and the environment*. Geneva, Switzerland, WHO. [Cited 30 June 2025]. https://www.who.int/publications/i/item/9789240059139

**Wiedemann, S.G., Biggs, L., Nebel, B., Bauch, K., Laitala, K., Klepp, I. G., Swan, P. G. & Watson, K.** 2020. Environmental impacts associated with the production, use, and end-of-life of a woollen garment. *The International Journal of Life Cycle Assessment*, 25, 1486–1499. https://link.springer.com/article/10.1007/s11367-020-01766-0

**Wilkinson, A.D. & Meeker, D.** 2021. How agricultural rendering supports sustainability and assists livestock's ability to contribute more than just food. *Animal Frontiers*, 11(2): 24–34. https://doi.org/10.1093/af/vfab002

**Wilkinson, J. & Lee, M.R.F.** 2018. Use of human-edible animal feeds by ruminant livestock. *Animal*, 12(8): 1735–1743. https://doi.org/10.1017/S175173111700218X

**Wilkinson, J.M.** 2011. Re-defining efficiency of feed use by livestock. *Animal*, 5(7): 1014–1022. https://doi.org/10.1017/S175173111100005X

**Woodgate, S.L.** 2023. Meat industry by-products: A bio-refinery approach to the production of safe, value added products for sustainable agriculture applications. *Frontiers in Animal Science*, 4, 1259200. https://doi.org/10.3389/fanim.2023.1259200

**Woodgate, S.L. & Wilkinson, R.G.** 2021. The role of rendering in relation to the BSE epidemic, the development of EU animal by-product legislation and the reintroduction of rendered products into animal feeds. *Annals of Applied Biology*, 178(3): 430–441. https://doi.org/10.1111/aab.12676

**Woodgate, S. & Van de Veen, J.** 2004. The role of fat processing and rendering in the European Union animal production industry. *Biotechnologie, Agronomie, Société et Environnement*, 8(4): 283–294. [Cited 20 July 2025]. https://popups.uliege.be/1780-4507/index.php?id=17416&file=1&pid=14194

**WRO (World Renderers Organization).** 2023. International report: 2023 WRO General Assembly and other collaborations. *Render Magazine*, August 2023. https://worldrenderers.net/wp-content/uploads/2024/10/2023-08.pdf

**Wu, H., Hanna, M.A. & Jones, D.D.** 2013. Life cycle assessment of greenhouse gas emissions of feedlot manure management practices: Land application versus gasification. *Biomass and Bioenergy*, 54, 260–266. https://doi.org/10.1016/j.biombioe.2013.04.011

**Wu, S., Thapa, B., Rivera, C. & Yuan, Y.** 2021. Nitrate and nitrite fertilizer production from air and water by continuous flow liquid-phase plasma discharge. *Journal of Environmental Chemical Engineering*, 9(2): 104761. https://doi.org/10.1016/j.jece.2020.104761

**Xiang, W., Zhang, X., Chen, J., Zou, W., He, F., Hu, X., Tsang, D.C., Ok, Y.S. & Gao, B.** 2020. Biochar technology in wastewater treatment: A critical review. *Chemosphere*, 252, 126539. https://doi.org/10.1016/j.chemosphere.2020.126539

**Xing, H., Cheng, J., Tan, X., Zhou, C., Fang, L. & Lin, J.** 2020. Ag nanoparticles-coated cotton fabric for durable antibacterial activity: Derived from phytic acid–ag complex. *The Journal of The Textile Institute*, 111(6): 855–861. https://doi.org/10.1080/00405000.2019.1668137

**Xuan Dung, N.N., Manh, L.H., Thanh Lam, N.N. & Kamada, T.** 2010. Effects of sugar cane syrup on performance and digestibility of growing-finishing pigs. *Livestock Research for Rural Development*, 22(8). https://www.lrrd.cipav.org.co/lrrd22/8/xdun22145.htm

**Yadav, K.D., Tare, V. & Ahammed, M.M.** 2012. Integrated composting–vermicomposting process for stabilization of human faecal slurry. *Ecological Engineering*, 47, 24–29. https://doi.org/10.1016/j.ecoleng.2012.06.039

**Yang, L., Si, B., Tan, X., Xu, J., Xu, W., Zhou, L., Chen, J., Zhang, Y. & Zhou, X.** 2022. Valorization of livestock manure for bioenergy production: A perspective on the fates and conversion of antibiotics. *Resources, Conservation and Recycling.*, 183, 106352. https://doi.org/10.1016/j.resconrec.2022.106352

**Yang, W. & Shen, Y.** 2018. Quality assessment of feed wheat in ruminant diets. In: S. Fahad, A. Basir & M. Adnan, eds. *Global wheat production*. 250 pp. London, IntechOpen. https://doi.org/10.5772/intechopen.75588

**Yang, X., Blagodatsky, S., Lippe, M., Liu, F., Hammond, J., Xu, J. & Cadisch, G.** 2016. Land-use change impact on time-averaged carbon balances: Rubber expansion and reforestation in a biosphere reserve, South-West China, Forest Ecology and Management. *Forest Ecology and Management*, 372, 149–163. https://doi.org/10.1016/j.foreco.2016.04.009

**Yaşar, S. & Forbes, J.M.** 2001. In vitro estimation of the solubility of dry matter and crude protein of wet feed and dry. *Turkish Journal of Veterinary and Animal Sciences*, 25(2): 149–154. [Cited 30 June 2025]. https://journals.tubitak.gov.tr/veterinary/vol25/iss2/2

**Yoo, G., Lee, Y.O., Won, T.J., Hyun, J.G. & Ding, W.** 2018. Variable effects of biochar application to soils on nitrification-mediated $N_2O$ emissions. *Science of the Total Environment*, 626, 603–611. https://doi.org/10.1016/j.scitotenv.2018.01.098

**Zandona, E., Blažić, M. & Režek Jambrak, A.** 2021. Whey utilization: Sustainable uses and environmental approach. *Food Technology and Biotechnology*, 59(2): 147–161. https://doi.org/10.17113%2Fftb.59.02.21.6968

**Zhao, S., Schmidt, S., Gao, H., Li, T., Chen, X., Hou, Y., Chadwick, D., Tian, J., Dou, Z., Zhang, W. & Zhang, F.** 2022. A precision compost strategy aligning composts and application methods with target crops and growth environments can increase global food production. *Nature Food.*, 3(9): 741–752. https://doi.org/10.1038/s43016-022-00584-x

**Zheng, Y., Wang, B., Wester, A.E., Chen, J., He, F., Chen, H. & Gao, B.** 2019. Reclaiming phosphorus from secondary treated municipal wastewater with engineered biochar. *Chemical Engineering Journal*, 362, 460–468. https://doi.org/10.1016/j.cej.2019.01.036

**Zijlstra, R.T.** 2021. Use of fermentation co-products in pet food and animal feeds. *Journal of Animal Science*, 99(3): 64–65. https://doi.org/10.1093/jas/skab235.116

**Zikeli, S., Deil, L. & Möller, K.** 2017. The challenge of imbalanced nutrient flows in organic farming systems: A study of organic greenhouses in Southern Germany. *Agriculture, Ecosystems & Environment*, 244, 1–13. https://doi.org/10.1016/j.agee.2017.04.017

**Zohairi, S.Al., Knudsen Trydeman, M. & Mogensen, L.** 2023. Utilizing animal by-products in European slaughterhouses to reduce the environmental footprint of pork products. *Sustainable Production and Consumption*, 37, 306–319. https://doi.org/10.1016/j.spc.2023.03.005

# Appendices

Appendix 1

# Energy values of plant-based products

## FEDNA METHODOLOGY

These equations have been developed to calculate the energy values of feed ingredients based on their chemical composition as well as the gross energy (GE) and digestibility coefficients assigned to each nutrient. These coefficients are estimations based on literature and presented in a simplified format according to ingredient type.

### Ruminants

Digestible energy (DE) value per kg of ingredient for ruminants is estimated using the following prediction equation, based on as-fed values:

DE (kcal/kg) = crude protein (CP, g/kg) x 5.65**(1)** kcal gross energy (GE)/g x dCP**(2)** + ether extract (EE, g/kg) x 9.4**(3)** kcal GE/g x dEE**(4)** + neutral detergent fibre (NDF, g/kg) x 4,2 kcal GE/g x dNDF/100**(5)** + starch (STR, g/kg) x 4.1 kcal GE/g x 0.95**(6)** + sugars (SGR, g/kg) x 3.8 kcal GE/g**(7)** + difference (DIF)**(8)** (g/kg) x 4.0 kcal GE/g x 0.90**(9)**

**(1)** Except for protein concentrates of animal origin = 5.7 kcal/g.
**(2)** CP digestibility values assigned to each ingredient in the tables.
**(3)** For protein concentrates of animal origin = 9.5 and for dairy products = 9.3 kcal/g.
**(4)** Estimated digestibility values of EE: 95% for corn and bakery wastes; 85% for other cereal grains and corn co-products; 40% for wheat milling co-products and 70% for other cereal co-products; 90% for lupins and 95% for beans and whole oilseeds and expellers; 70% for protein meals, grain legumes or pulses and fibrous co-products.
**(5)** NDF digestibility = 68% for cereal grains, except for oats and hulls (50%). For other feed ingredients, estimates have been calculated using the Cornell Net Carbohydrate and Protein System (CNCPS) model [(NDF – 2.4 x acid detergent lignin (ADL)/NDF] (Sniffen *et al.*, 1992), except for bean and soybean hulls, citrus pulp (85%), carob (45%), cereal straws and lentils (40%), olive co-products (25%) and grape co-products (10-15%).
**(6)** Starch digestibility is assumed to be 95% for all feed ingredients.
**(7)** Sugar digestibility is assumed to be 100% for all feed ingredients.
**(8)** Difference (DIF) between 1 000 and the weight in grams of [moisture + ash + CP + EE + NDF + STR + SGR], except for olive co-products where DIF = 0.
**(9)** Estimated digestibility value of DIF fraction.

In the second step, the metabolizable energy (ME)/DE ratios and energy utilization efficiencies (K) for lactation (Kl), maintenance (Km), growth (Kg), along with maintenance and growth (Kmg) are calculated for a production level [net energy for growth (NEg)/(net energy for maintenance (NEm) + NEg)] of 1.5 using equations proposed by INRA (2018):

ME/DE (%) = 86.38 – 0.099 CF0 – 0.196 CP0,

where CF0 = % crude fibre (CF)/OM and CP0 = % CP/OM.

Net energy for lactation (NEl)/ME (Kl) = 0.60 + 0.24 (ME/GE – 0.57); NEl (kcal/kg) = ME x Kl;

NEm/ME (Km) = 0.287 ME/GE + 0.554;

NEm (kcal/kg) = ME x Km;

NEg/ME (Kg) = 0.78 ME/GE + 0.006;

NEmg/ME (Kmg) = [Km x Kg x 1.5]/[Kg + 0.5 Km];

NEg (kcal/kg) = ME x Kmg.

Finally, *unité fourragère* – forage unit in the INRA system (INRA, 2018) – for lactation (UFl) and *unité fourragère* for growth (UFg) per kg of feed ingredient is calculated using the following formulas:

UFl = (DE x ME/DE x Kl)/1 700 UFg = (DE x ME/DE x Kmg)/1 820

NEl, NEm and NEg values in the NRC system (NCR, 2001) are estimated for feeding at 3 x maintenance level and the ME is calculated using the following equations for ME, NEl, NEm and NEg (megacalories [Mcal]/kg DM) from the NRC tables for concentrated feeds:

NEl/ME (%) = 2.7391 x ME (Mcal/kg DM) + 55.993;

NEl (kcal/kg) = ME x Kl;

NEm/ME (%) = 1.7958 x ME (Mcal/kg DM) + 63.283;
NEm (kcal/kg) = ME x Km;
NEg/ME (%) = 5.8317 x ME (Mcal/kg DM) + 28.932;
NEg (kcal/kg) = ME x Kmg

## Swine

For swine, DE for growth (DEg) of a feed ingredient on an as-fed basis can be estimated using the following formula:

DEg (kcal/kg) = CP (g/kg) x 5.65**(1)** (kcal GE/g) x dCP**(2)** + EE (g/kg) x 9.4**(3)** (kcal GE/g) x dEE**(4)** + NDF (g/kg) x 4.2 (kcal GE/g) x dNDF**(5)** + starch (STR, g/kg) x 4.1 (kcal GE/g) x dSTR **(6)** + sugars (SGR, g/kg) x 3.8 (kcal GE/g)**(6)** x dSGR(6) + DIF**(7)** (g/kg) x 4.0 (kcal GE/g) x 0.85**(8)**.

**(1)** Except in protein concentrates of animal origin = 5.7 kcal/g.
**(2)** According to values assigned to each ingredient in the tables.
**(3)** In protein concentrates of animal origin = 9.5 and in dairy products = 9.3 kcal/g.
**(4)** EE digestibility: 80% for corn and sorghum grains, corn gluten and cereal co-products containing more than 3.5% EE; 60% for all other grains and cereal co-products; 80–90% for plant protein concentrates, higher for co-products with higher free fat, except lupine (60%); 30% for fibrous co-products, except olive pulp (90%).
**(5)** NDF digestibility: 55% for cereal grains, except for oats (35%); 45% for corn co-products, 34–40% for wheat milling co-products, increasing with starch level; 35% and 40% for barley and wheat dried distiller grains, respectively; in plant protein concentrates the equation [88.0 – 1.56 x % ADL/% NDF] is used, except for sunflower (30–35%) and palm kernel meals (50%); 25–30% for alfalfa meals, increasing with the CP level; 10–20% for lignified fibrous co-products of carob, sunflower, olive, grape and cereal straws; 60% for soybean hulls and 80% for sugar beet and citrus pulps.
**(6)** Starch and sugar digestibility values are assumed to be 98% and 100%, respectively, for all feeds, except for starches obtained from grain legumes and pulses (95%).
**(7)** Difference between 1 000 and the weight in grams of [moisture + ash + CP + EE + NDF + STR + SGRs], except for olive co-products where DIF = 0.
**(8)** Average digestibility estimated for DIF fraction.

ME and NE values were calculated using the equations proposed by Noblet, Shi and Dubois (1994) for growing pigs (NEg). For adult pigs, NE values were estimated using the equation of Le Goff and Noblet (2001).

ME/DE = 100.7 – 0.021 CP (g/kg DM) – 0.005 NDF (g/kg DM);
NE (kcal/kg) = 0.73ME (kcal/kg) + 13.1 EE (%) + 3.7 SGR (%) – 6.7 CP (%) – 9.7 CF (%).

## Poultry

For poultry, the apparent metabolizable energy (AME) values of feed ingredients on an as-fed basis can be estimated using the following formula:

AME (kcal/kg) = CP (g/kg) x 5.65**(1)** (kcal GE/g) x 0.80**(2)** x dCP**(3)** + EE (g/kg) x 9.4 (kcal GE/g)**(4)** x dEE**(5)** + NDF (g/kg) x 4.2 (kcal GE/g) x 0.05**(6)** + starch (STR, g/kg) x 4.1 (kcal GE/g) x dSTR **(7)** + sugars (SGR, g/kg) x 3.8 (kcal GE/g) x dSGR**(7)** + DIF**(8)** (g/kg) x 4.0 (kcal GE/g) x 0.10**(9)**

**(1)** Except in protein concentrates of animal origin = 5.7 kcal/g.
**(2)** Correction factor to account for energy losses through urine.
**(3)** CP digestibility values assigned to each ingredient, based on values from similar feed ingredients in the relevant tables (e.g. Spanish Foundation for the Development of Animal Nutrition – Fundación Española para el Desarrollo de la Nutrición Animal [FEDNA]).
**(4)** In protein concentrates of animal origin = 9.5 and in dairy products = 9.3 kcal/g.
**(5)** Estimated average digestibility of EE = 85% for all feed ingredients, except corn gluten, bakery wastes, oilseeds and extruded soybeans (90–95%).
**(6)** Estimated average digestibility of NDF.
**(7)** Digestibility of starches and sugars is assumed to be 100% for all feed ingredients except for rye, wheat milling co-products and rice bran (95%), grain legumes (pulses) and fibrous co-products (90%), and for sugars in dairy products (70%).
**(8)** Difference between 1 000 and the weight in grams of [moisture + ash + CP + EE + NDF + Starch+ SGR].
**(9)** Average digestibility estimated for DIF fraction.

## ALTERNATIVE METHODOLOGY, WHEN THE DIGESTIBILITY COEFFICIENTS OF THE CO-PRODUCTS ARE UNKNOWN

### Ruminants

Prediction equations OMd (in %) from chemical composition (in g/kg DM):

- Cereals and co-products: OMd = 92.2 - 0.149 x CF + 0.0074 x CP – 0.050 x ash
- Oil seeds and co-products: OMd = 89.6 – 0.106 x CF + 0.0088 x CP – 0.003 x ash
- Legume seeds: OMd = 92.6 – 0.031 x CF
- Co-products of grapes and olives: OMd = 63.6 – 0.089 x CF
- Fruit residues (i.e. apple, tomato, pineapple, pumpkin) OMd = 89.3 – 0.094 x CF.

Prediction equations of the digestibility of energy (Ed in %) from OMd (%):

- Ed = −3.5 + OMd + 0.046 x CP + 0.0155 x EE (INRA, 2018).

Further analysis can be undertaken as described in the section on FEDNA methodology.

### Swine

- DE (kcal/kg) = 4.168 – (91 x % ash) + (19 x % CP) + (39 x % Cfat) – (36 x % NDF) (Noblet and Perez, 1993)
- ME (kcal/kg) = DE – (6.8 x % CP) (Noblet and Perez, 1993)
- NE (kcal/kg) = 0.730 x ME + 13.15 x % EE + 3.59 x % Starch – 6.69 x % CP – 9.8 x %CF (Noblet, Shi and Dubois, 1994).

### Poultry

- MJ/kg of ME = 0.1551 × % CP + 0.3431 × % EE + 0.1669 × % starch + 0.1301 × % SGR (expressed as sucrose) ), or
- AMEn(kcal/g) = 3.411 + 0.045 x EE (% DM) – 0.073 CF (% DM) – 0.035 ash (% DM)

(Campbell, Classen and Ballance, 1986).

## ABBREVIATIONS

| | |
|---|---|
| ADL | acid detergent lignin |
| AME | apparent metabolizable energy |
| CP | crude protein |
| DE | digestible energy |
| DIF | difference |
| DM | dry matter |
| ED | energy digestibility (percentage of energy that is digestible) |
| EE | ether extract |
| GE | gross energy |
| K | energy utilization efficiency |
| ME | metabolizable energy |
| NDF | neutral detergent fibre |
| NE | net energy |
| OM | organic matter |
| SGRs | sugars |
| STR | starch |
| UF | forage unit in the INRA system |
| D | digestible |
| G | growth |
| L | lactation |
| M | maintenance |
| mg | maintenance and growth complex |

Appendix 2

# Nutritional values of the main plant-based products used as feed ingredient

This table provides detailed information on the nutritional values, benefits and disadvantages of the main co-products currently used as feed ingredients.

TABLE A2.1

**Characteristics of plant-based co-products used as feed for livestock**

| SOURCE: PROCESS/INDUSTRY | POTENTIAL/NUTRITIONAL VALUE | BENEFICIAL EFFECTS | ANIMAL | DISADVANTAGES | REFERENCE |
|---|---|---|---|---|---|
| FERMENTATION | | | | | |
| Brewery | | | | | |
| Brewer's spent grain | • DM basis 20% protein, essential amino acids and phenolic compounds | • increased milk yield, higher fat content in milk | • ruminants/ pigs/ chickens/fish | • high moisture content: 70%/ limited storage/ rapid microbiological degradation | Ikram *et al.*, 2017 |
| Brewer's yeast (Saccharomyces) | • protein-rich, high nucleic acid content (RNA) | • dried yeasts are an excellent source of protein for swine and ruminants | • ruminants/swine /fish | • High moisture content 86–90%/ bitter taste | Ferreira *et al.*, 2010 |
| Bioethanol/biofuel production | | | | | |
| Corn distillers' grain such as dried distillers' grain with solubles (DDGS) | • 31% protein, 11% fat, 7% fibre and 6% ash | • easily digestible source of fibre, suitable for replacing forage in animal diets<br>• in aquaculture, improved feed intake, feed conversion ratio and weight gain | • maximum inclusion for ruminants (20–40%), pigs (20–50%) and poultry (10–15%) | • variation in nutritional quality and physical characteristics | Doppenberg and Van Der Aar, 2007 |
| Condensed distillers' soluble (CDS) | • water concentration can vary from 50% to 80% as is, and CP ranges between 20% and 30% on a dry matter basis | • rich in protein, fibre and essential amino acids<br>• including CDS in the diet improves ruminal fermentation by increasing the number of starch and lactic acid using bacteria<br>• source of supplemental protein | • maximal animal performance for beef was between 20.8% and 32.5% of diet dry matter<br>• CDS containing up to 15% fat depending on the source | • because CDS are liquid they require special equipment<br>• very short shelf-life<br>• variation in nutritional quality and physical characteristics | Yaşar and Forbes, 2001 |
| Vinasses (condensed molasses solubles) or molasses | • pH around 4.5, high viscosity and about 65% dry matter<br>• low in sugar but relatively high amount of protein and minerals<br>• DM content ~45–60%, CP 6–13%, ash 15%, with considerable amount of macrominerals and microminerals | • improves digestibility and efficiency of feed for cattle<br>• increases feed intake and the survival rate of animals at times of food shortage<br>• improved average daily weight gain of calves | • ruminants, pigs and poultry<br>• in cattle feed, vinasse could be used up to 10–15%<br>• in growing pigs, it could be used up to 30% | • higher viscosity and potassium level<br>• viscosity can be reduced by adding steam during processing but higher potassium, when consumed, is detrimental to animals | Hannon and Trenkle, 1990; Chen, Chen and Wang, 2022 |
| INDUSTRY | | | | | |
| Biodiesel | | | | | |
| Wheat DDGS | • CP: 33.6%<br>• fat: 4.8%<br>• fibre: 7.6% | • used as an energy source owing to its highly digestible fibre and moderate level of fat | • ruminants, pigs, poultry | • variable protein quality<br>• wheat DDGS has a relatively small impact on carcass quality because of the lower fat content | Blas Beorlegui *et al.*, 2021 |

*(Cont.)*

TABLE A2.1 *(Cont.)*

**Characteristics of plant-based co-products used as feed for livestock**

| SOURCE: PROCESS/INDUSTRY | POTENTIAL/NUTRITIONAL VALUE | BENEFICIAL EFFECTS | ANIMAL | DISADVANTAGES | REFERENCE |
|---|---|---|---|---|---|
| Rapeseed meal | • CP: 31–35%<br>• fat: 2.5%<br>• fibre: 11–15% | • excellent protein source owing to its relatively high protein level (30–40%), lysine, methionine and tryptophan levels | • ruminants (dairy/beef) 1–4 kg, fattening pigs and sows (20–25%)<br>• used for cattle, pigs, poultry | • erucic acid, sinapin, glucosinolates<br>• relatively low digestibility | Doppenberg and Van Der Aar, 2007; Nega and Woldes, 2018; Spek and Blok, eds, 2018 |
| Rapeseed cake/ expeller | • CP: 31.6%<br>• fat: 11.1%<br>• fibre: 12.1% | | | | |
| Glycerin/glycerol | • energy value of crude glycerin is similar to that of corn grain, estimated at 3.47 Mcal/ kg DM for ruminants | • sweet taste, improves efficiency of feed use, because of a decrease in the acetic/propionic ratio in the rumen<br>• in ruminants, the potential of glycerin to prevent acidosis has been indicated<br>• reported reduction in methane production | • ruminants (15%), pigs (5%), poultry (10%) | • methanol presence and high in salt<br>• variable levels of methanol can be found, ranging from 1.3% to 27% | Doppenberg and Van Der Aar, 2007 |
| Sugar production industry | | | | | |
| Beet pulp | • sugar-beet pulp (SBP) consists of up to 75% w/w carbohydrates (DM basis)<br>• after sugar extraction, the pressed pulp has a DM content of 18–23% w/w<br>• relatively low in crude protein (8%) but relatively high in total digestible nutrients (TDN) (72%) | • works very well to support underweight horse, cattle, sheep or goat diets, being a high calorie (providing energy without excess sugar), supplemental feed ingredient<br>• can be used effectively as a supplement for gestating or lactating cows<br>• a natural sponge, it has an incredible ability to absorb water<br>• safeguards against impaction colic | • horses, cattle | • no more than 50% of the ration (DM basis) as beet pulp<br>• natural Imbalance of beet pulp: high in calcium but tends to be lower in phosphorus | Kühnel, Schols and Gruppen, 2011; Berlowska *et al.*, 2018 |
| Molasses | • DM: 77–78%<br>• CP: 6.7% (cane)/13.5% (beet)<br>• sucrose: 48.8–60.9%<br>• total sugars: 51–71% | • palatable and excellent energy source<br>• improved production in ruminants<br>• stimulates dry matter intake (DMI)<br>• rapidly fermented and digested | • ruminants, pigs, poultry | • not fully characterized in the literature<br>• variable organic acids and mineral content | Palmonari, 2020 |
| Starch production industry | | | | | |
| Wheat gluten feed, gluten meal, germ meal | • germ meal<br>• CP: 26–35%<br>• fat: 10–15%<br>• sugar: 17%<br>• fibre: 1.5–4.5%<br>• minerals: 4%<br>• gluten feed<br>• CP (mainly gliadins and glutenins): 16%<br>• fat: 4%<br>• fibre: 6.9%<br>• gluten meal<br>• CP: 75%<br>• fat: 4.6%<br>• fibre: 5.2% | • wheat has a low amount of fibre, which facilitates the digestive processes in ruminants, poultry and pigs | • wheat is an excellent feed ingredient for polygastric animals, such as ruminants, and for monogastric animals | • wheat should be processed to improve its digestibility<br>• proper feed management is critical | Yang and Shen, 2018; Van Soest, Robertson and Lewis, 1991; Brandolini and Hidalgo, 2012; Spek and Blok, eds, 2018 |

*(Cont.)*

TABLE A2.1 *(Cont.)*

**Characteristics of plant-based co-products used as feed for livestock**

| SOURCE: PROCESS/INDUSTRY | POTENTIAL/NUTRITIONAL VALUE | BENEFICIAL EFFECTS | ANIMAL | DISADVANTAGES | REFERENCE |
|---|---|---|---|---|---|
| Maize/corn gluten feed, gluten meal and germ meal | • corn gluten feed<br>• DM: 88%<br>• CP: 21%<br>• fat 2%<br>• fibre: 10%<br>• minerals and amino acids, corn gluten meal (on a DM basis):<br>• CP: 60-75%<br>• starch: 15-20%<br>• fat: 3%<br>• minerals: 2%<br>• fibre: 1% | • corn gluten feed offers medium protein and high energy for ruminants<br>• palatable, low-starch product, high in rumen degradable protein, vitamins B, phosphorus and highly digestible fibre | • ruminant, poultry, swine and pet foods | • feeding large amounts of corn gluten feed can lead to sulphur toxicity, resulting in reduced feed intake and risk of toxicity | Heuzé *et al.*, 2015a; Spek and Blok, eds, 2018; Batal and Dale, 2016 |
| Maize/corn gluten meal and germ meal | • CP: 60%<br>• fat: 5.6%<br>• fibre: 1% | | | | |
| Maize/corn germ feed expeller | • CP: 13.4%<br>• fat: 5.6%<br>• fibre: 5.9% | | | | |
| Potato protein | • CP: 78.5%<br>• fat: 3.1%<br>• fibre: 0.8% | • potatoes are high in rapidly digestible starch (70% of DM) | • ruminants, poultry, swine and pet foods | • fermentation in the rumen; acidosis maybe a problem<br>• less than 50% in diet<br>• low palatability for sheep<br>• boiled for monogastric animals | Pavlista and Rush, 2002; Spek and Blok, eds, 2018 |
| Potato pulp | • CP: 10–12%, with a high biological value score (70–90) and high lysine content | | | | |
| Grain milling for flour production | | | | | |
| Wheat bran | On a dry matter basis:<br>• CP: 14-19%<br>• starch: 15–30%<br>• fibre: 7–14%<br>• oil: 3–5%<br>• minerals: 4–7% | • good source of protein, thiamin, riboflavin and potassium, and a very good source of dietary fibre, niacin, pyridoxine, iron, magnesium, phosphorus, zinc, copper, manganese and selenium | • suitable for ruminants, horses and some monogastric animal species (poultry) as a source of fibre and micronutrients | • should be stored in a cool, dry place to prevent rancidity | Heuzé *et al.*, 2015b |
| Wheat middlings | • CP: 28.89%<br>• fibre: 9.48%<br>• neutral detergent fibre (NDF): 41.86% | • higher fibre, lower starch content compared to other flour mill residues<br>• less digestible but may have gut health benefits | • all livestock<br>• fibre and energy source for ruminants<br>• up to 50% concentrate replacement for cattle<br>• fed without enzymes up to 30% in pigs and broilers with no production loss | • may require exogenous enzymes for optimal monogastric animal response | NRC, 2012; Casas *et al.*, 2018; Bernard, 1995; Ahmadi and Amini, 2014; ZoBell *et al.*, 2003 |
| Rice bran | • CP: 14%<br>• NDF: 12%<br>• acid detergent fibre (ADF) and fibre: 3–4%<br>• fat: 14–18%<br>• starch: 42% but varies depending on processing | • palatable, good source B vitamins<br>• high in lysine (Lys) and methionine (Met)<br>• good manganese (Mn) bioavailability | • all livestock as an energy source, but inclusion rates vary depending on basal diet<br>• broilers only up to 15% (20% with enzymes)<br>• 22–60% inclusion for pigs as basal diet | • variable composition depending on processing and blends of co-products from milling<br>• only about 10% yield from grain<br>• rancidifies rapidly if not dried<br>• high fibre and phytate may decrease use for poultry<br>• can decrease DMI and digestibility in ruminants | Heuzé *et al.*, 2015c |

*(Cont.)*

TABLE A2.1 *(Cont.)*

**Characteristics of plant-based co-products used as feed for livestock**

| SOURCE: PROCESS/INDUSTRY | POTENTIAL/NUTRITIONAL VALUE | BENEFICIAL EFFECTS | ANIMAL | DISADVANTAGES | REFERENCE |
|---|---|---|---|---|---|
| Oil crushing | | | | | |
| Sunflower seed meal | • CP: 30–40% DM<br>• fibre: 12–30% DM<br>• depends on the dehulling process<br>• lignin: 9–12%<br>• fat: <2% | • generally a valuable and safe product, whose protein, fibre and oil contents are highly variable and driven by variations in the oil extraction process | • valuable livestock feed ingredient, particularly for ruminants and rabbits, and – under certain conditions – for pigs and poultry | • fresh sunflower meal must be dried for optimal storage<br>• high moisture levels can be a challenge | Heuzé *et al.*, 2019 |
| Sunflower seed expeller/cake | • CP: 30–40% DM<br>• fibre: 12–30% DM<br>• depends on the dehulling process<br>• lignin: 9–12%<br>• fat: 7–10% | | | | |
| Palm kernel expeller/cake | • DM: 90%,<br>• CP: 17%<br>• metabolizable energy (ME): 11.7 MJ<br>• NDF: >60%<br>• fibre: 17.5%<br>• fat: 8–10%<br>• NDF: 54% | • palm oil and palm-kernel oil can be used instead of butterfat in milk replacers to feed young animals, as a substitute for their mother's milk<br>• increased energy levels in the diet of dairy cows can benefit the production of milk and milk components, improve reproductive efficiency, reduce heat stress, and improve general animal health and well-being<br>• increasing fat/oil levels in pig diets improves growth rates, reproduction and lactation. | • cattle, pigs | • high in fibre content, reduced intake | Akinyeye *et al.*, 2011; Spek and Blok, eds, 2018 |
| Palm kernel meal | • CP: 15.8%<br>• fat: 2.4% Fat<br>• fibre: 17.3% | | | | |
| Linseed meal | • CP: 30–39% DM, relatively poor in lysine (about 4% of the protein)<br>• fibre: 8–14% DM<br>• particularly high in omega-3 | • adding linseed meal to ruminant diets is likely to increase the concentration of polyunsaturated fatty acids (PUFAs) in dairy products and beef<br>• the omega-3 can reduce the risk of cardiovascular diseases<br>• may help to reduce methane | • cattle, buffalo, sheep and swine | • deficient in lysine, methionine and threonine, lower CP-level linseed meal is laxative when fed in large amounts<br>• contains two types of toxic factors: (i) a dipeptide called linatine composed of glutamic acid and (ii) L-amino-D-proline, an antagonist of pyridoxine (vitamin B)<br>• in non-ruminants, linseed meal may produce pyridoxine toxicity | Mills *et al.*, 2011; Spek and Blok, eds, 2018 |
| Peanut meal | • solvent extracted<br>• CP: 48%<br>• 1.9% fat expeller<br>• CP: 45.2%<br>• fat: 9% | • high protein, high oil<br>• may help to reduce methane | • all livestock | • risk of aflatoxins | Hill, 2002; Zhao *et al.*, 2023 |

*(Cont.)*

TABLE A2.1 *(Cont.)*

**Characteristics of plant-based co-products used as feed for livestock**

| SOURCE: PROCESS/INDUSTRY | POTENTIAL/NUTRITIONAL VALUE | BENEFICIAL EFFECTS | ANIMAL | DISADVANTAGES | REFERENCE |
|---|---|---|---|---|---|
| Olive meal and cake | • olive cake<br>• good fat content (16%), but high fibre content, very lignified and low protein value<br>• olive cake, partially defatted<br>• fat: 11.9%<br>• olive meal<br>• fat: 0.5% | • rich in oleic acid | • ruminants | | Blas Beorlegui *et al.*, 2021; Manzanares *et al.*, 2017 |
| Groundnut meal and cake | • CP: 45.2–48%<br>• fat: 1.9—9% | • very good protein source that can be an alternative to soybean meal | • all species | • traditionally associated with aflatoxin-related issues, but there are now safe meals on the market | Blas Beorlegui *et al.*, 2021 |
| Cottonseed meal and cake | Whole cottonseed:<br>• CP: 20.7–23%<br>• fat: 11–19.2 %<br>Cottonseed expeller, partly dehulled:<br>• CP: 36.3 %<br>• fat: 7.4%<br>• fibre: 17% | • the correlation between elevated-protein and increased-energy content allows to develop cost-effective diet formulations | • ruminants | • presence of gossypol | Lima *et al.*, 2014; Riaz *et al.*, 2023; Spek and Blok, eds, 2018 |
| Fruit processing | | | | | |
| Citrus pulp | • CP: 6–8%<br>• fat: 1–9%<br>• fibre: 9–17%<br>• sugar: 24% | • highly palatable ingredient<br>• can be used fresh, ensiled or dehydrated | • ruminants | • low CP<br>• low digestibility that decreases with high dehydration temperatures | Spek and Blok, eds, 2018; Blas Beorlegui *et al.*, 2021 |
| Orange Bagasse | • CP: <10–35% soluble carbohydrates/low lignin: <5% | • combined with other protein-rich coproducts, allows to develop cost-effective diet formulations | • ruminants | | Bizzuti *et al.*, 2023 |
| Former food (discarded because no longer suited for human consumption) | | | | | |
| Supermarket residual | • DM: 22.1%<br>• CP: 22.1%<br>• fat: 36.6%<br>• variable minerals and fibre | • intended for human consumption but have become unsaleable (cosmetic reasons, past sell by date)<br>• nutritional value | • all species, given proper processing | • variation in nutrient content, packaging, handling and processing logistics | Dou, 2021; Jinno *et al.*, 2018 |
| Food residuals from restaurant and household | • DM: 21.7%<br>• CP: 19.2%<br>• fat: 21.5%<br>• fibre: 6.2%nitrogen-free extract (NFE): 24.4% | • high nutritional value, but unsuitable for human consumption or unpalatable | • all species, given proper processing | • processing and feeding regulations not standardized<br>• infrastructure for handling and storage often a barrier<br>• potential quality issues | Dou, Toth and Westendorf, 2018 |
| Biscuits meal | • CP: 8.3%<br>• fat: 10%<br>• fibre: 0.5% | • recycling of expired or discarded food products<br>• the base of this ingredient is usually wheat flour<br>• high palatability | • all species, given proper processing | • special attention should be given to the rancidity of the fat fraction<br>• theobromine content (if there is cocoa in the mixture)<br>• processing conditions | Spek and Blok, eds, 2018; Blas Beorlegui *et al.*, 2021 |
| Other food industry co-products | | | | | |
| Beans and soybean hulls | • CP: 23%<br>• soluble carbohydrates: 42% | • the correlation between protein content and soluble carbohydrate content allows for the development of cost-effective diet formulations | • ruminants | | Bizzuti *et al.*, 2023 |

*Notes:* CP = crude protein, DM = dry matter, DMI = dry matter intake, ME = metabolizable energy, NDF = neutral detergent fibre, NFE = nitrogen-free extract.
*Source:* Authors' own elaboration.

# Appendix 3
# Examples of plant-based products

Examples of PBPs used in livestock feeding around the world are listed in what follows, prior to considering region-specific cases.

***Euphorbia heterophylla*** is a weed found both in Africa and Asia. In West Africa (Côte d'Ivoire, Ghana, southern Nigeria), it poses a serious problem because of its ability to thrive in a wide range of crops. In Côte d'Ivoire, it is found in 70 percent of the cotton fields (Ipou *et al.*, 2004). *Euphorbia heterophylla* reaches maturity within about 45 to 50 days and, as a result, it can have several reproductive cycles per year. Bindelle *et al.* (2007) showed that it is high in crude protein (16 to 27 percent of dry matter [DM]) and oil content (7.7 percent of DM) but low in fibre (22 percent of DM). *Euphorbia heterophylla* is also high in omega-3 fatty acids and can be used to partially replace soybean meal (SBM) in the diets of guinea pigs, rabbits and poultry (Kouakou *et al.*, 2013, 2016).

***Hevea brasiliensis***, commonly known as the rubber, yields a milky latex that serves as the primary source of natural rubber. Its global distribution is pantropical. Rubber seed meal has no adverse effect on animal performance. It contains relatively high contents of essential amino acids and omega-3 polyunsaturated fatty acids, and it can replace SBM in the diet. According to Nwokolo (1996), the Rubber Research Institute of Nigeria estimates that seed yield from rubber plantations ranges from 100 to 150 kg/ha, depending on soil fertility and crop density. In countries that cultivate the rubber tree for latex, the almost freely available seeds can act as a valuable protein and oil source. Oil can be extracted from the seeds to obtain a meal. Mechanically pressed meals can be found in many tropical countries. The first studies devoted to rubber seed meal go back to the 1970s. Experiments have been conducted mainly with cattle and, to a lesser extent, with pigs and poultry (Rajaguru and Ravindran, 1979; Viswanathan and Ananthasubramaniam, 1977). *Hevea brasiliensis* produces cyanogenic glycosides, which are concentrated in the seeds. Once detoxified through heating, rubber seed meal can serve as feed for pigs (Madubuike, Ekenyem and Obih, 2006; Kouakou *et al.*, 2018), cockerels (Ravindran, Kornegay and Rajaguru, 1987) or laying hens (Harnentis and Syahruddin, 2016) and guinea fowl (Koné, Good and Kouba, 2020; Koné *et al.*, 2022; Kouassi *et al.*, 2020). Rubber seed oil can also be used as a feed ingredient (Wen *et al.*, 2019; Liu *et al.*, 2022). A high percentage of polyunsaturated fatty acids in the diet has been reported to lower plasma cholesterol or affect cholesterol distribution between tissues and plasma (Grundy and Ahrens, 1970; Kellogg, 1974; Koné, Good and Kouba, 2020; Kouassi *et al.*, 2020).

**Cashew nuts** (*Anacardium occidentale L.*) deemed unfit for human consumption are typically discarded and can be purchased at a low cost. Bouaffou *et al.* (2011) review the use of cashew nuts in chicks, pullets and finishing broiler chickens, growing rabbits, cattle and growing pigs. More recent studies have examined their use in pigs (Yao *et al.*, 2013; Kouakou *et al.*, 2018), rabbits (Gomes *et al.*, 2020), lambs (Costa *et al.*, 2021), chickens (Fernandes *et al.*, 2016; Akande and Gbadamosi, 2020; Vidal *et al.*, 2013; Cruz *et al.*, 2015), guinea fowl (Koné, Good and Kouba, 2020; Koné *et al.*, 2022) and fish (Iheanacho *et al.*, 2019; Ogueji *et al.*, 2020). Cashew nut oil has also been fed to broiler chickens (Odunsi and Oyewole, 1996)

***Cassava*** (*Manihot esculenta*) residues can be successfully incorporated into feed, with co-products readily available in the vicinity of factories that process cassava tubers into starch or flour. Turning agricultural residuals such as cassava peels into a feed ingredient promotes circular bioeconomy principles by closing nutrient loops and preventing pollution. Peels can be grated, dewatered, pulverized, sun-dried or dried (Okike *et al.*, 2015). Cassava co-products can be used to generate biogas, providing a clean energy source for cassava processing and reducing reliance on firewood and the resulting deforestation. Furthermore, using slurry from biodigesters as organic fertilizer reduces the need for chemical fertilizer. Co-product fractions differ in their nutrient profiles: leaves and green fractions are considered rich in protein, while the remaining constituents are used as sources of dietary energy (Table A3.1).

**Macadamia *(Macadamia* spp.)** nuts are mainly destined for human consumption and command a high price. Except for rejected nuts, they are unlikely to be used in feed. The oil- and protein-rich macadamia oil cake has potential as a feed ingredient. Macadamia oil is usually extracted using cold-press methods (i.e. below 30 °C). The extraction yields a golden yellow oil that has a low peroxide index (antioxidant property) but is prone to rancidity. Cold-pressed macadamia oil cake can be used as food or feed (Navarro and Rodrigues, 2016).

**Jatropha *(Jatropha cuneata)*** oil extracted from seeds can be processed into biodiesel. The oil can also be used as

TABLE A3.1
**Defined fractions of cassava *(Manihot esculenta)* used in livestock feeding programmes**

| Definition, processing method, form or use |
|---|
| Fresh or wilted leaves, chopped or intact; can include the petiole or not |
| Dried leaf fractions, chopped or ground; can include the petiole or not |
| Protein precipitate from leaves, processed using heat and/or acid |
| Includes leaf, petiole and stems, generally >40 cm from soil surface |
| Also known as starch residue, pulp, or bagasse, is the solid fibrous residue that remains after starch has been extracted from the root. It can make up to 17% of a tuber's fresh weight. Its quality and appearance vary depending on the tuber's age, the time elapsed after harvest and the type of industrial equipment used |
| Obtained after peeling and cleaning with water; can represent 5–15% of tuber weight |
| Root fractions, cut chunks of varying size; can contain both pulp and peel |
| Dried root tissue |
| Ends trimmed off the tubers prior to washing and peeling |
| Various fractions processed into pellets |
| Liquid pressed out of the tuber, after it has been crushed mechanically; whey and pomace can be mixed to form slurry or effluent |
| Tubers that fail to meet the quality standards for processing may be mixed with stumps, which are often higher in fibre content |
| A co-product of *garri* (also spelled *gari*, *gary*) production. Tubers are peeled, crushed, fermented, sieved and roasted. Cassava sievate represents approximately 15–17% of the root weight |
| Purified starch extracted from cassava tuber pulp |
| Pellets Include flour made from whole root (including peel), leaves and petioles |

*Sources:* Balagopalan *et al*., 1988; Cereda and Mattos 1996; Boscolo, Hayashi and Meurer, 2002a, 2002b; Nwokoro, Vaikosen and Bamgbose, 2005; Furlan *et al*., 2005; Ukachukwu, 2005; Modesti, 2007; Aro, 2010. See Appendices in References.

a fuel for oil lamps or cooking. Generated during oil extraction, Jatropha seed cake may serve as a fertilizer and as a feed ingredient, once detoxified. Unlike other major biofuel crops, such as corn, soybean and rapeseed, Jatropha is not used for food, and it can be grown on marginal and degraded lands. The leaves and nuts of *Jatropha curcas* are toxic as they contain phorbol esters. *Jatropha curcas* seed cake or meal cannot be directly used as a feed ingredient as it contains phorbol esters (Linden, 2012). The biodetoxification of *Jatropha curcas* seed cakes reduces phorbol ester levels and increases its nutritional value. Detoxified *Jatropha curcas* seed cake can constitute up to 20 percent of diet DM for growing goats (Kasuya *et al.*, 2012).

## SUB-SAHARAN AFRICA

In Africa, the intensification of food production in smallholder systems has generated vast quantities of food co-products and residuals (Waldron, 2007). With this came mounting social and environmental pressure to use agricultural industry residuals more efficiently (Pfaltzgraff *et al.*, 2013; Santana-Méridas, González-Coloma and Sánchez-Vioque, 2012). Using agro-industrial by-products as feed for livestock reduces the environmental impact of the food industry while making agricultural by-products more valuable and profitable, since feed is an efficient way of turning low-quality inputs into high-quality food products (Elferink, Nonhebel and Moll, 2008). The growing industrialization of food production in Africa is generating large quantities of food residues and losses that can be classified into six categories (Ajila, *et al.*, 2012):

1. crop residuals
2. fruit and vegetable co-products
3. sugar, starch and confectionary industry co-products
4. oil industry co-products
5. grain and legume co-products
6. distillery and brewery co-products

## MEDITERRANEAN AREAS

**Olive *(Olea europaea)*** trees rank among the oldest cultivated trees in the world. Around 20 million tonnes of olives are produced annually, mainly in the Mediterranean region, which accounts for 50 percent of this output (AtlasBig, 2023). Pruning olive trees generates a large amount of biomass, which is mainly used to generate energy. Olive oil extraction gives rise to several co-products, including pomace, pits and leaves. Composed of olive skin, pulp, seed and pit fragments, olive pomace is the main co-product of the olive oil extraction (Manzanares *et al.*, 2017). Berbel and Posadillo (2018) have classified olive co-products into three categories, based on their economic value:

1. low-value co-products, consisting of highly lignified materials such as thin branches; wood and olive pits, used for thermal energy production and electricity generation;
2. medium-value co-products, suitable for use as animal feed; and
3. high-value co-products, the source of bioactive compounds such as hydroxytyrosol.

Olive pomace is first dried and then pitted to separate the olive pits, resulting in a co-product with a high oil content (i.e. on average 16 percent). Olive pomace can be marketed as such or partially deoiled. To facilitate handling, the pulp can be pelleted, with molasses often being added to facilitate pelleting and improve palatability. Olive pomace contains a substantial amount of highly lignified fibre. Its protein value is low, as a large portion of it (up to 80 percent) is bound to acid detergent fibre, which limits microbial degradation in the rumen and reduces protein availability to the animal (Blas Beorlegui *et al.*, 2021). Whole and partially deoiled olive pomace is used as an energy source in diets because of its high oil content. The high degree of lignified fibre in olive co-products limits their use, especially for monogastric livestock, but they can be included in diets at modest levels. Sánchez *et al.* (2022) reported that including olive pomace at 10 percent in a feed formulation for gestating Iberian sows had no adverse effects on growth or litter size, while its antioxidant properties contributed to improved gut health. Ferrer *et al.* (2020) included 12 percent olive pomace in the diet of finishing pigs with no negative effects on performance, carcass quality, gut microflora or gas emission from manure slurry; on the contrary, it improved the monounsaturated fatty acid concentration of subcutaneous fat. Olive pomace has been included at high levels (70 percent) in the diet of ewe and goats (Heuzé *et al.*, 2015d).

In their review, Tzamaloukas, Neofytou and Simitzis (2021) concluded that olive pomace increases monounsaturated fatty acids and decreases saturated fatty acids in ruminant milk and meat, with potential health benefits for consumers. Feeding costs were reduced with no detrimental effects on ruminal fermentation, nutrient use, growth performance, carcass traits, milk yield or composition. Bionda *et al*. (2022) fed olive pomace at levels up to 15 percent of the diet DM to finishing beef cattle. In Mediterranean buffalo, the inclusion of olive pomace at 10 percent of DM intake improved the fatty acid profile and nutritional characteristics of mozzarella cheese, with no negative effects on animal health or milk yields. Terramoccia *et al.* (2013) found that 1 kg DM per head improved milk quality and reduced the oxidation of fatty acids.

Olive leaves are a co-product derived from tree pruning or separating the leaves mixed with the olives during harvest. The main component of olive leaves is a highly lignified neutral detergent fibre, which reduces its nutritional value. The polyphenol content is also high, resulting in a bitter taste, although olive leaves are known for their antioxidants properties. Olive leaves are used as a source of fibre for ruminants and rabbits (Blas Beorlegui *et al.*, 2021). The physical structure of the fibre is similar to that of cereal straw. When feeding olive leaves to sheep, it is important to bear in mind the risk of copper contamination, especially if the trees have been treated with copper-based antimicrobials.

It is recommended to feed the olive leaves fresh, since their nutritional value is higher than that of dried or ensiled leaves. Separating the leaves from the wood is also advisable since the latter is better employed for producing energy through combustion (FAO, 1985). Another option, in integrated systems combining livestock and olive oil production, is direct browsing. The trees are browsed after olive harvest, and only during winter and spring. Ruminants (mainly sheep) are allowed to enter the olive tree fields and browse freely (Heuzé *et al.*, 2015d).

# Appendix 4
# Indigenous knowledge

Around the world, many Indigenous Peoples have a distinctive understanding of nature–rooted in cultural experience – that shapes relations between humans and non-humans within specific ecosystems. This understanding and these relations constitute a system broadly identified as Indigenous knowledge (IK), also known as traditional or Aboriginal knowledge. A cornerstone of Indigenous Peoples' cultural identity, IK applies to phenomena spanning biological, physical, social, cultural and spiritual systems as well as resource use practices (Bruchac, 2014). It includes sophisticated philosophies and practical measures aimed at preserving cultural heritage, while protecting ancestral landscapes and ways of living (Apffel-Marglin, 2011). This intimate relationship with nature allows Indigenous Peoples to perceive subtle microchanges and to base decisions on a deep understanding of patterns and processes of change in the natural world of which people are an integral part.

Indigenous knowledge is diverse and encompasses oral narratives of human histories; cosmological observations and ways of reckoning time; symbolic modes of communication related to techniques for planting and harvesting; hunting and gathering skills; specific knowledge related to local ecosystems; and the manufacture of specialized tools and technologies (e.g. flint-knapping, hide tanning, pottery-making or the preparation of medicinal remedies). Continually evolving to keep up with new ethnoknowledge, IK informs decision-making about fundamental aspects of Indigenous Peoples' day-to-day life.

### KNOWLEDGE TRANSFER

Some aspects of IK are shared across communities, while others are more localized and specific to particular groups, families and even individuals who are designated as custodians of traditional knowledge. Much of this knowledge is acquired through direct, lived experience and by engaging in everyday activities. A significant portion of IK relates to regenerative practices, in which waste is minimized through a circular bioeconomy rooted in cultural, spiritual and ecological knowledge.

Indigenous communities have developed distinctive methods for preserving and transmitting useful information within their worldviews and modes of activity, closely connected to particular landscapes. This knowledge is often passed down through oral traditions, song, dance and ceremonies that convey – both literally and metaphorically – important truths about the relationship between plants and animals, land and water, and supernatural forces.

Since IK fosters a deep connection with nature, it is relevant for all human systems. Studies also suggest that most of the world's remaining intact ecosystems are inhabited by communities that have maintained a close relationship with nature (OSTP, 2022). Because of this close connection to nature, Indigenous communities have long championed sustainability and instinctively followed circular bioeconomy principles. This is why the bioeconomy is increasingly seen as a point of convergence between IK and modern biomass processing technologies, working together to produce bio-based products and add value to biological resources, while addressing interconnected societal and environmental challenges.

### NEW TRENDS AND WAY FORWARD

There is now a broad recognition that IK offers more than just insights into past practices; it informs new protocols and agreements aimed at safeguarding Indigenous natural resources, cultural knowledge and intellectual property. The protection of Indigenous rights, including guaranteed access to traditional landscapes and more culturally sensitive resource management, has become a central concern in international environmental law (Bicker *et al.*, 2003; Menzies, ed., 2006). The concept of intellectual property has been extended to include oral traditions, folklore, ecological knowledge, Indigenous languages and traditional names.

In 2007, the General Assembly adopted the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP), which recognizes Indigenous ownership of ancestral lands, territories and natural resources and validates traditional practices as contributing towards the "sustainable and equitable development and proper management of the environment" (p. 4). In Canada, mainstream scientists have since reached out to Aboriginal knowledge-keepers and First Nations' tribal leaders to develop joint strategies to address climate change, habitat loss and environmental degradation caused by resource extraction and unsustainable development. In 2022, the White House Office of Science and Technology Policy (OSTP) and the Council on Environmental Quality acknowledged through their joint *Guidance for Federal Departments and Agencies on Indigenous Knowledge* that taking IK into account is essential for making sound scientific and policy decisions at the federal level.

To fully engage IK in support of a circular bioeconomy, the following recommendations are made:

- establish an IK institute to support the use of IK and technologies in research to produce bio-based products and services in support of a circular bioeconomy;
- create incentives for industry/private sector to invest in IK research and innovations that promote the efficient use, reuse, recycling and upcycling of bioresources;
- strengthen interactions between academia, research, local communities, industry and government to foster economic and social development;
- support innovative uses of traditional medicines and IK;
- encourage the effective use of bioscience-related IK;
- promote aromatherapy and the production of essential oils;
- document and share IK while respecting the values of its original owners; and
- recognize the unique value of IK within a circular bioeconomy.

## ETHNOVETERINARY PRACTICE

Deeply rooted in traditional cultures, the use of PBPs is an integral part of livestock husbandry in many societies around the globe (Table A4.1). Herbal remedies offer an alternative to conventional antimicrobials for treating livestock diseases (Mayer *et al*., 2014). The use of extracts or whole medicinal plants is widespread among some livestock producers (Lans *et al*., 2000) and is increasingly promoted as a sustainable practice (Mayer *et al*., 2014).

To effectively support and promote ethnoveterinary practices, the following actions are recommended:

- establish a central body tasked with developing policies and programmes to popularize ethnoveterinary medicine;
- set up regional centres for the collection and documentation of information on ethnoveterinary practices in collaboration with stakeholders;
- support interdisciplinary ethnoveterinary research that illustrates the efficacy, technical know-how, socioeconomic benefits and cost-effectiveness of ethnoveterinary practice;
- promote *ex situ* conservation, for example by establishing botanical gardens to preserve endangered medicinal plants, thereby supporting a sustainable system of conservation and medicinal plant use;
- respect and recognize the traditional medical knowledge present in different cultures;
- share benefits equitably with the local communities who contributed to the research outcomes; and
- develop memoranda of understanding to foster clarity and trust in ethnoveterinary research collaborations.

TABLE A4.1
**Most commonly used ethnoveterinary co-products**

| Plant species/Common name | Family | Ethnoveterinary uses |
|---|---|---|
| *Cannabis sativa*<br>Marijuana | Cannabaceae | anthelmintic, diarrhoea, dysentery, cough, cold, veterinary problems, urinary problems, flatulence, stomach ache, swollen stomach |
| *Asparagus racemosus*<br>Wild asparagus | Asparagaceae | stomach pain, colic, mastitis, bone problems, treating worms in hoof and stomach, placenta removal, lactation stimulant |
| *Schima wallichii*<br>Needlewood tree | Theaceae | taeniasis, stomach disorders, anthelmintic, diarrhoea, cough |
| *Alstonia scholaris*<br>Blackboard tree | Apocynaceae | nutritious feed ingredient, improves fertility, diarrhoea, dysentery, tonic, fever, improves lactation, increases strength and vigour |
| *Lindera neesiana*<br>Himalayan spicebush | Lauraceae | diarrhoea, dysentery, antidote, placenta removal, tonic, indigestion, ectoparasites |
| *Senna tora*<br>Sickle senna | Fabaceae | treatment for hair loss, fever, anthelmintic, veterinary medicine |
| *Colebrookea oppositifolia*<br>Indian squirrel tail | Lamiaceae | conjunctivitis, cataract, corneal opacity, anthelmintic, veterinary diseases, removing leeches from nostril |
| *Achyranthes aspera*<br>Prickly chaff flower | Amaranthaceae | veterinary medicine, cure for endoparasites, eases delivery, accelerates placenta expulsion, stimulates lactation |
| *Boenninghausenia albiflora*<br>White Himalayan rue | Rutaceae | treating ectoparasites, wounds, insecticide, antidiabetic |
| *Cuscuta reflexa*<br>Dodder | Convolvulaceae | pneumonia, asthma, cough, throat allergy, indigestion, stomach disorders, endoparasites, pain, fever, dysentery |
| *Millettia extensa*<br>Large leaf pongam creeper | Fabaceae | antiectoparasitic, veterinary medicine, scabies |
| *Lyonia ovalifolia*<br>Fetterbush | Ericaceae | skin diseases, can cause alkaloid poisoning |
| *Oxalis* spp.<br>Shamrock | Oxalidaceae | earache, body swelling, veterinary medicine, boils, eye problems, muscular swelling |
| *Pyrus pashia*<br>Wild Himalayan pear | Rosaceae | lactation, eye problems, including cataract, constipation |
| *Solena amplexicaulis*<br>Creeping cucumber | Cucurbitaceae | lactation, veterinary medicine, mastitis, intestinal worms |
| *Bombax ceiba*<br>Red cotton tree | Bombacaceae | veterinary medicine, boils, constipation, dysentery, placenta removal, indigestion, dislocated bones, cuts and wounds |
| *Datura metel*<br>Devil's trumpet | Solanaceae | diarrhoea, dysentery, fever, inflammation, wounds, joint swelling, sleep inducing |
| *Nicotiana tabacum*<br>Tobacco | Solanaceae | skin disease, antiectoparasitic, wounds, fever |
| *Pogostemon benghalensis*<br>Bengal shrub mint | Lamiaceae | dysentery, veterinary medicine, wounds, cough, bronchitis |
| *Prunus persica*<br>Peach | Rosaceae | treating cuts, wounds, bone dislocation, endoparasites |
| *Stephania glandulifera*<br>Elephant dropping plant | Menispermaceae | veterinary problems, tonic, stomach disorder, diarrhoea |
| *Acorus calamus*<br>Sweet flag | Acoraceae | repellent, indigestion, cough, fever |
| *Azadirachta indica*<br>Indian lilac | Meliaceae | anthelmintic, cuts, wounds |
| *Boehmeria virgata var. macrostachya*<br>False nettle | Urticaceae | diarrhoea, dysentery, cuts, wounds |

*(Cont.)*

TABLE A4.1 *(Cont.)*

**Most commonly used ethnoveterinary co-products**

| Plant species/Common name | Family | Ethnoveterinary uses |
|---|---|---|
| *Clerodendrum infortunatum*<br>Hill glory bower | Lamiaceae | veterinary medicine, lice removal, intestinal worms, stomach swelling, wounds |
| *Ficus religiosa*<br>Bo tree | Moraceae | foot-and-mouth disease, rheumatism, urinary problems, treating burns, fever |
| *Rumex nepalensis*<br>Nepal dock | Polygonaceae | antidote, dislocated bones, diarrhoea, tonic |
| *Tinospora cordifolia*<br>Heart-leaved moonseed | Menispermaceae | cures sterility, improves lactation, appetite loss, cough, constipation, diarrhoea |
| *Urtica dioica*<br>Stinging nettle | Urticaceae | improves lactation, cures mastitis, urinary problems, sprains |
| *Viscum album*<br>Mistletoe | Viscaceae | dislocated bones, wounds, veterinary disease, treats swelling, boils |
| *Zingiber officinale*<br>Ginger | Zingiberaceae | foot-and-mouth disease, fever, diarrhoea, mastitis, wounds, cough |

*Source:* Uprety, Y., Karki, S., Poudel, R.C. & Kunwar, R.M. 2022. Ethnoveterinary use of plants and its implication for sustainable livestock management in Nepal. *Frontiers in Veterinary Science*, 9, 930533. https://doi.org/10.3389/fvets.2022.930533

# Appendix 5
# Use of whey and scotta in animal feeding

Feeding livestock dairy co-products can be beneficial in terms of sustainability and increased economic efficiency, particularly in cases where these co-products would otherwise be discarded (e.g. whey and scotta in certain regions; Section 3.2.2.1). The main advantages are:

- reduced feed costs, which represent the largest expense in livestock farming;
- water conservation, especially when whey or scotta is used to partially replace drinking water;
- lower fixed costs related to waste disposal;
- improved efficiency resulting from greater circularity.

A critical issue for whey, especially for sweet whey (pH >5.0), is its limited shelf-life. In the past, formalin was often used to stabilize whey for use in animal feed (Fisher, 1981), a practice that has largely been discontinued. More recently, sweet whey has been stabilized through inoculation with probiotic bacteria (Figure A5.1) and used as a biopreservative to prevent the growth of fungi in poultry feed (Londero *et al.*, 2014). Milk whey has been included in the diet of ruminants at up to 30 percent, but a two-week adaptation period is recommended to prevent bloating (Schingoethe, 1975, 1981). Research has shown that growing cattle can be fed up to 98 percent of whey silage (ZoBell *et al.*, 2004) without adverse effects on daily gain, intake and feed use efficiency. Its use as feed for cattle and buffalo lowers diet costs with no negative impacts on calf performance and digestion; in fact, it increases milk fat content in dairy cattle. Dried and liquid whey have also been used successfully in lambs, sheep and goats with no detrimental effects observed (Lupo *et al.*, 2019; Andersen and Aalund, 1975).

Goats fed whey showed improvements in yield, fat content and rheological characteristics (Rapetti *et al.*, 1995). Andersen and Aalund (1975) observed acceptable rates of gain in heifers fed nothing but whey. Performance improved when the ration was based on whey and concentrate, with daily increases greater than 1 kg/day. Although it is quite low in protein, whey may be considered a concentrate for ruminants because of its lactose and fat content. To prevent excessive rumen acidification, the amount of whey administered should be adjusted based on the overall diet composition and feeding method. Estimates suggest that ruminants can consume 12–15 L of fresh whey per 100 kg of liveweight

TABLE A5.1
**Recommended or applied levels of liquid whey in the diet of various livestock species**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Fattening pigs | 20 kg LW | | 40 g LW | 50 kg LW | 60 kg LW | >70 kg LW | |
| | 1 L/d | | 6 L/d | 8 L/d | 12 L/d | 13 L/d | |
| Large ruminants | Calves | | Young steers | | Cows | | |
| Cattle | 6–8% (max. 15%) LW<br>25–30% feed intake (DM base) | | Up to 50% feed intake (DM base) | | 6–8 % (max. 15%) LW<br>15–18% feed intake (DM base) | | |
| Buffalo | Pre-weaning | Post-weaning | Up to 40% feed intake (DM base) | | Heifers up to 6 months pregnancy | Lactating | Dry |
| | 5–7% (max. 12%) LW<br>20–% feed intake (DMbase) | 4–8 L/d | | | 40–50 L/d | 20–40 L/d | Max. 10 L/d |
| Small ruminants | Lambs[1] | | Sheep[2] | | Goats[3] | | |
| | 2–2.5% LW | | 10% LW<br>7–9 L/d | | 10% LW<br>5–6 L/d | | |

*Notes:* LW = liveweight; L/d = litre per day; DM = dry matter.

[1] Lupo, C.R., Grecco, F.C. de Almeida Rego, Eleodoro, J.I., Cunha Filho, L.F. Coelho, Serafim, C.C., Dos Santos, J. Sifuentes, Ludovico, A., De Almeida, M., Ferreira, Zundt, M., Garrido, J. Volpato & Hernandes, C. 2019. Viability of the use of bovine milk whey at lamb finishing: Performance, carcass, and meat parameters. *Journal of Applied Animal Research*, 47(1): 449–453. https://doi.org/10.1080/09712119.2019.1653302

[2] Andersen, H. & Aalund, O. 1975. Intensive animal production in Denmark: Some environmental aspects. *Agriculture and Environment*, 2(1): 65–73. https://doi.org/10.1016/0304-1131(75)90006-5

[3] Rapetti, L., Falaschi, U., Lodi, R., Vezzoli, F., Tamburini, A., Greppi, G.F. & Enne, G. 1995. The effect of liquid whey fed to dairy goats on milk yield and quality. *Small Ruminant Research*, 16(3): 215–220. https://doi.org/10.1016/0921-4488(95)00637-Z

*Source:* Authors' own elaboration.

(Thivend, 1977).

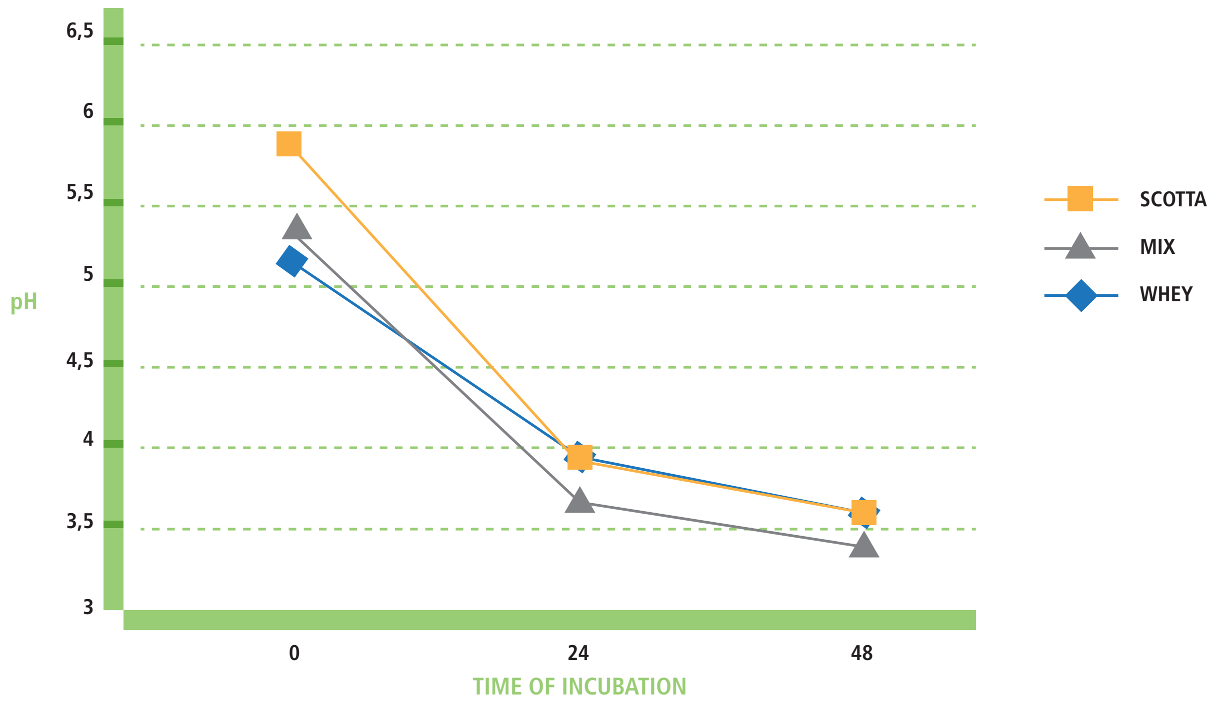
Lactose is readily fermented to lactic acid in the rumen, lowering rumen pH (Rémond and Coulon, 1986). If the lactic acid accumulates in the rumen, it can result in acidosis (Thivend, 1977). Whey may be fed directly mixed with other dietary ingredients (Table A5.1). In pigs the ideal ratio is 4–6 kg whey per kg feed. Scotta tends to be fed to pigs, but an effective use of a whey–scotta mix has been reported also for veal calves.

TABLE A5.2
**Average chemical composition* and pH of fresh whey and scotta**

| Parameter (%) | Whey | Scotta |
|---|---|---|
| Dry matter | 6.52 | 5.93 |
| Lactose | 4.32 | 4.59 |
| Protein | 0.86 | 0.41 |
| Fat | 0.19 | 0.17 |
| Ash | 0.51 | 0.87 |
| pH | 5.94 | 6.08 |

* Composition may vary as a function of the cheese production processing, reference species and season.
*Source:* Authors' own elaboration.

FIGURE A5.1
**Acidification of whey, scotta and a 50:50 whey–scotta mix with *Lactobacillus helveticus* for direct livestock feeding: pH vs incubation time in hours**




*Source:* Authors' own elaboration.

## REFERENCES


**Ahmadi, K. & Amini, B.** 2014. Determination of chemical composition and suitable level of wheat middlings in broiler diets. *International Journal of Plant, Animal and Environmental Sciences*, 4(2): 454–459. https://www.fortunejournals.com/ijpaes/admin/php/uploads/540_pdf.pdf

**Ajila, C.M., Brar, S.K., Verma, M. & Prasada Rao, U.J.S.** 2012. Sustainable solutions for agro processing waste management: An overview. In: A. Malik & E. Grohmann, eds. *Environmental protection strategies for sustainable development*, pp. 65–109. New York, USA, Springer Nature. https://doi.org/10.1007/978-94-007-1591-2_3

**Akande, T.O. & Gbadamosi, F.A.** 2020. Feeding value of defatted cashew kernel as an alternative protein source in broiler diets. *Nigerian Journal of Animal Production*, 45(5): 39–45. https://doi.org/10.51791/njap.v45i5.486

**Akinyeye, D.R.** 2011. Physico-chemical properties and anti-nutritional factors of palm fruit products (*Elaeis guineensis* Jacq.) from Ekiti State Nigeria. *Journal of Environmental, Agricultural and Food Chemistry*, 10(6): 333–340. https://www.academia.edu/28218096/Physico_Chemical_Properties_and_Anti_Nutritional_Factors_of_Palm_Fruit_Products_Elaeis_Guineensis_JACQ_from_Ekiti_State_Nigeria

**Andersen, H. & Aalund, O.** 1975. Intensive animal production in Denmark: Some environmental aspects. *Agriculture and Environment*, 2(1): 65–73. https://doi.org/10.1016/0304-1131(75)90006-5

**Apffel-Marglin, F.** 2011. *Subversive spiritualities: How rituals enact the world*. Oxford, UK, Oxford University Press.

**Aro, S.O., Aletor, V.A., Tewe, O.O. & Agbede, J.O.** 2010. Nutritional potentials of cassava tuber wastes: A case study of a cassava starch processing factory in south-western Nigeria. *Livestock Research for Rural Development*, 22(11), paper No. 2013. https://lrrd.cipav.org.co/lrrd22/11/aro22213.htm

**AtlasBig.** 2023. World olive production by country. In: *AtlasBig*. [Cited 30 June 2025]. https://www.atlasbig.com/en-us/countries-olive-production

**Balagopalan, C.** 1988. Cassava in food, feed and industry. CRC press. https://doi.org/10.1201/9781351070430

**Barnhardt, R. & Kawagley, A.O.** 2005. Indigenous knowledge systems and Alaska native ways of knowing. *Anthropology & Education Quarterly*, 36(1): 8–23. https://doi.org/10.1525/aeq.2005.36.1.008

**Batal, A.B. & Dale, N.M.** 2016. *Feedstuffs ingredient analysis table*. Athens, USA, Feedstuffs. https://www.yumpu.com/en/document/read/68310904/feedstuffs-ribg-ingredient-analysis-table-2016

**Berlowska, J., Binczarski, M., Dziugan, P., Wilkowska, A., Kregiel, D. & Witońska, I.** 2018. Sugar beet pulp as a source of valuable biotechnological products. In: A.M. Holban & A.M. Grumezescu. eds. *Advances in biotechnology for food industry: Volume 14*, pp. 359–392. Amsterdam, Elsevier. https://doi.org/10.1016/B978-0-12-811443-8.00013-X

**Berbel, J. & Posadillo, A.** 2018. Review and analysis of alternatives for the valorisation of agro-industrial olive oil by-products. *Sustainability*, 10(1): 237. https://doi.org/10.3390/su10010237

**Bernard, S.** 1995. Some aspects of in vitro regeneration of bread wheat. *Agronomie*, 15(7–8): 499–500. https://doi.org/10.1051/agro:19950729

**Bindelle, J., Ilunga, Y., Delacollette, M., Mulund Kayij, M., di M'Balu, J. Umba, Kindele, E. & Buldgen, A.** 2007. Voluntary intake, chemical composition and *in vitro* digestibility of fresh forages fed to Guinea pigs in periurban rearing systems of Kinshasa (Democratic Republic of Congo). *Tropical Animal Health and Production*, 39(6): 419–426. https://doi.org/10.1007/s11250-007-9036-y

**Bionda, A., Lopreiato, V., Crepaldi, P., Chiofalo, V., Fazio, E., Oteri, M., Amato, A. & Liotta, L.** 2022. Diet supplemented with olive cake as a model of circular economy: Metabolic and endocrine responses of beef cattle. *Frontiers in Sustainable Food Systems*, 6, 1077363. https://doi.org/10.3389/fsufs.2022.1077363

**Bizzuti, B.E., Pérez-Márquez, S., Van Cleef, F. de Oliveira Scarpino, Ovani, V.S., Costa, W. Santos da, Lima, P. de Mello Tavaeres, Louvandini, H. & Abdalla, A.L.** 2023. In vitro degradability and methane production from by-products fed to ruminants. *Agronomy*, 13(4): 1043. https://doi.org/10.3390/agronomy13041043

**Blas Beorlegui, C. de, García Rebollar, P., Gorrochategui, M., Mateos, G.G., Cegarra, E., Méndez, J., Santomá, G., Pérez de Ayala, P., Solà-Oriol, D. & Calsamiglia Blancafort, S.** 2021. *FEDNA tables on the composition and nutritional value of raw material for the production of compound animal feed*. 571 pp. Madrid, FEDNA (Fundación Española para el Desarrollo de Nutrición Animal – Spanish Foundation for the Development of Animal Nutrition). [Cited 30 June 2025]. https://www.todostuslibros.com/libros/fedna-tables-on-the-composition-and-nutritional-value-of-raw-materials-for-the-production-of-compound-animal-feeds-4th-edition_978-84-09-35781-9

**Boscolo, W.R., Hayashi, C. & Meurer, F.** 2002a. Digestibilidade aparente da energia e nutrientes de alimentos convencionais e alternativos para a tilápia do Nilo (*Oreochromis niloticus*, L.). *Revista Brasileira de Zootecnia*, 31(2): 539–545. https://doi.org/10.1590/S1516-35982002000300001

**Boscolo, W.R., Hayashi, C. & Meurer, F.** 2002b. Farinha de varredura de mandioca (*Manihot esculenta*) na alimentação de alevinos de tilápia do Nilo (*Oreochromis niloticus*, L.). *Revista Brasileira de Zootecnia*, 31(2): 546–551. https://doi.org/10.1590/S1516-35982002000300002

**Bouafou, K.G.M., Konan B.A., Zannou-Tchoko, V. & Kati-Coulibally, S.** 2011. Cashew in breeding: Research synthesis. *International Journal of Agronomy & Agricultural Research*, 1(1): 1–8. https://innspub.net/wp-content/uploads/2022/01/IJAAR-V1-No1-p1-8.pdf

**Brandolini, A. & Hidalgo, A.** 2012. Wheat germ: Not only a by-product. *International Journal of Food Sciences and Nutrition*, 63(sup1): 71–74. https://doi.org/10.3109/09637486.2011.633898

**Bruchac, M.M.** 2014. Indigenous knowledge and traditional knowledge. In: C. Smith, ed. *Encyclopaedia of global archaeology*, pp. 3814–3824. New York, USA, Springer Nature. https://doi.org/10.1007/978-1-4419-0465-2_10

**Campbell, G.L., Classen, H.L. & Ballance, G.M.** 1986. Gamma irradiation treatment of cereal grains for chick diets. *The Journal of Nutrition*, 116(4): 560–569. https://doi.org/10.1093/jn/116.4.560

**Casas, G., Jaworski, N., Htoo, J. & Stein, H.** 2018. Ileal digestibility of amino acids in selected feed ingredients fed to young growing pigs. *Journal of Animal Science*, 96(6): 2361–2370. https://doi.org/10.1093/jas/sky114

**Cereda, M.P. & Mattos, M.C.Y.** 1996. Linamarin: The toxic compound of cassava. *Journal of Venomous Animals and Toxins*, 2(1): 6–12. https://doi.org/10.1590/S0104-79301996000100002

**Chan, H.-Y., Yen, J.-H., Chen, D.-Y., Tsay, T.-T. & Chen, P.** 2016. The occurrence, identification and ecological studies of the cactus nematode from dragon fruit crops in Taiwan. *Journal of Plant Medicine*, 58(1): 25–31. https://doi.org/10.6716/JPM.201603_58(1).0004

**Chen, Y.-H., Chen, C.-Y. & Wang, H.-T.** 2022. The effect of forage source and concentrated liquid feedstuff supplementation on improving the synchronization of ruminant dietary energy and nitrogen release in vitro. *Fermentation*, 8(9): 443. https://doi.org/10.3390/fermentation8090443

**Costa, L.M., Chaudhry, U.N., Silva, C.R., Sousa, D.M., Silva, N.C., Cutrim-Júnior, J.A.A., Brito, D.R.B. & Sargison, N.D.** 2021. Nemabiome metabarcoding reveals differences between gastrointestinal nematode species infecting co-grazed sheep and goats. *Veterinary Parasitology*, 289, 109339. https://doi.org/10.1016/j.vetpar.2020.109339

**Cruz, F. Kleszcz da, Garcia, E.R. de Moraes, Ferraz, A.L.J., Souza, K.M. Ribeiro de, Feliciano, W. Britez & Rohod, R. Vilalba.** 2015. Quality and stability of eggs from laying hens fed with organic minerals and lycopene. *Ciência Rural*, 46(1): 157–162. https://doi.org/10.1590/0103-8478cr20150594

**De Leeuw, Egeru, A. & Okia, C.** 2014. Trees and livelihoods in Karamoja, Uganda. In: *GOV.UK*. London. https://doi.org/10.12774/eod_hd.december2014.egeruaetal

**Doppenberg, J., & Van der Aar, P., eds.** 2007. *Biofuels: Implications for the feed industry*. 118 pp. Wageningen, Kingdom of the Netherlands, Wageningen Academic Publishers. https://www.wageningenacademic.com/doi/book/10.3920/978-90-8686-617-5

**Dou, Z.** 2021. Leveraging livestock to promote a circular food system. *Frontiers of Agricultural Science and Engineering*, 8(1): 188–192. https://doi.org/10.15302/J-FASE-2020370

**Dou, Z., Toth, J.D. & Westendorf, M.L.** 2018. Food waste for livestock feeding: Feasibility, safety, and sustainability implications. *Global Food Security*, 17, 154–161. https://doi.org/10.1016/j.gfs.2017.12.003

**Elferink, E.V., Nonhebel, S. & Moll, H.C.** 2008. Feeding livestock food residue and the consequences for the environmental impact of meat. *Journal of Cleaner Production*, 16(12): 1227–1233. https://doi.org/10.1016/j.jclepro.2007.06.008

**FAO.** 1985. *Olive by-products for animal feed*. FAO Animal Production and Health Paper No. 43. Rome. [Cited 30 June 2025]. https://www.fao.org/4/x6545e/x6545e00.htm

**Fernandes, D.R., Freitas, E.R., Watanabe, P.H., Filgueira, T.M. Bezerra, Cruz, C.E. Braga, Do Nascimento, G.A.J., Aguiar, G.C. & Nascimento, E.R.M.** 2016. Cashew nut meal in the feeding of meat quails. *Tropical Animal Health and Production*, 48(4): 711–717. https://doi.org/10.1007/s11250-016-1008-7

**Ferrer, P., Calvet, S., García-Rebollar, P., De Blas, C., Jiménez-Belenguer, A. I., Hernández, P., Piquer, O. & Cerisuelo, A.** 2020. Partially defatted olive cake in finishing pig diets: Implications on performance, faecal microbiota, carcass quality, slurry composition and gas emission. *Animal*, 14(2): 426–434. https://doi.org/10.1017/S1751731119002040

**Ferreira, I.M.P.L.V.O., Pinho, O., Vieira, E. & Tavarela, J.G.** 2010. Brewer's *Saccharomyces* yeast biomass: Characteristics and potential applications. *Trends in Food Science & Technology*, 21(2): 77–84. https://doi.org/10.1016/j.tifs.2009.10.008

**Fisher, L.J.** 1981. The consumption of acid whey by lactating cows. *Canadian Journal of Animal Science*, 61(1): 209–211. https://doi.org/10.4141/cjas81-028

**Furlan, A.C., Scapinello, C., Moreira, I., Murakami, A.E., Santolin, M.L. da Rosa & Otutumi, L.K.** 2005. Avaliação nutricional da raspa integral de mandioca extrusada ou não para coelhos em crescimento. *Acta Scientiarum. Animal Sciences*, 27(1): 99–103. https://doi.org/10.4025/actascianimsci.v27i1.1258

**Gomes, T. Ribeiro, Freitas, E. Rodrigues, Watanabe, P.H., Sousa, A. da Rocha, Ferreira, A.C. Sampaio & Tavares, L.M. de Sousa.** 2020. Cashew nut meal (*Anacardium occidentale* L.) in the feeding of growing rabbits. *Ciência Animal Brasileira,* 21, e-61927. https://doi.org/10.1590/1809-6891v21e-61927

**Grundy, S.M. & Ahrens, E.H.** 1970. The effects of unsaturated dietary fats on absorption, excretion, synthesis, and distribution of cholesterol in man. *Journal of Clinical Investigation*, 49(6): 1135–1152. https://doi.org/10.1172/JCI106329

**Hannon, K. & Trenkle, A.** 1990. Evaluation of condensed molasses fermentation solubles as a nonprotein nitrogen source for ruminants. *Journal of Animal Science*, 68(9): 2634. https://doi.org/10.2527/1990.6892634x

**Harnentis, H. & Syahruddin, E.** 2016. Pengaruh temperatur steam dan suplementasi bakteri mannanolitik termofilik terhadap histomorfologi usus, retensi nitogen dan energi metabolisme ransum (pellet) broiler berbasis ampas kelapa. *Jurnal Peternakan Indonesia (Indonesian Journal of Animal Science)*, 18(1): 53. https://doi.org/10.25077/jpi.18.1.53-61.2016

**Heuzé, V., Tran, G. & Lebas, F.** 2015a. Maize germ meal and maize germ. In: *Feedipedia – Animal Feed Resources Information System*. Paris, INRAE–CIRAD–AFZ–FAO. [Cited 30 June 2025]. https://www.feedipedia.org/node/716

**Heuzé, V., Tran, G., Baumont, R., Noblet, J., Renaudeau, D., Lessire, M. & Lebas, F.** 2015b. Wheat bran. In: *Feedipedia – Animal Feed Resources Information System.* Paris, INRAE–CIRAD–AFZ–FAO. [Cited 30 June 2025]. https://www.feedipedia.org/node/726

**Heuzé, V., Tran, G., Bastianelli, D. & Lebas, F.** 2015c. Rice bran and other rice by-products. In: *Feedipedia – Animal Feed Resources Information System.* Paris, INRAE–CIRAD–AFZ–FAO. [Cited 30 June 2025]. https://www.feedipedia.org/node/750

**Heuzé, V., Tran, G., Gomez Cabrera, A. & Lebas, F.** 2015d. Olive oil cake and by-products. In: *Feedipedia – Animal Feed Resources Information System*. Paris, INRAE–CIRAD–AFZ–FAO. [Cited 30 June 2025]. https://www.feedipedia.org/node/32

**Heuzé, V., Tran, G., Hassoun, P., Lessire, M., Lebas, F.** 2019. Sunflower meal. In: *Feedipedia – Animal Feed Resources Information System*. Paris, INRAE–CIRAD–AFZ–FAO. [Cited 30 June 2025]. https://www.feedipedia.org/node/732

**Hill, G.** 2002. Peanut by-products fed to cattle. *Veterinary Clinics of North America: Good Animal Practice*, 18(2): 295–315. https://doi.org/10.1016/S0749-0720(02)00019-1.

**Ikram, S., Huang, L., Zhang, H., Wang, J. & Yin, M.** 2017. Composition and nutrient value proposition of brewers spent grain. *Journal of Food Science*, 82(10): 2232–2242. https://doi.org/10.1111/1750-3841.13794

**INRA (Institut national de la recherche agronomique – National Research Institute for Agricultural Research), ed.** 2018. *INRA feeding system for ruminants*. Wageningen, Kingdom of the Netherlands, Wageningen Academic Publishers. https://doi.org/10.3920/978-90-8686-292-4

**Ipou, J., Marnotte, P., Aman Kadio, G., Aké, S. & Touré, Y.** 2004. Influence de quelques facteurs environnementaux sur la germination des semences d'*Euphorbia heterophylla* L. (Euphorbiaceae). Conference presentation at Douzième colloque international sur la biologie des mauvaises herbes, 31 août–2 septembre 2004. Dijon, France, AFPP (Association française de protection des plantes). https://agritrop.cirad.fr/521539/

**IUCN (International Union for Conservation of Nature and Natural Resources), WHO (World Health Organization) & WWF (World Wide Fund for Nature).** 1993. *Guidelines on the conservation of medicinal plants*. Gland, Switzerland, IUCN. https://iris.who.int/bitstream/handle/10665/41651/2831701368_en.pdf?sequence=1

**Jinno, C., He, Y., Morash, D., McNamara, E., Zicari, S., King, A., Stein, H.H. & Liu, Y.** 2018. Enzymatic digestion turns food waste into feed for growing pigs. *Animal Feed Science and Technology*, 242, 48–58. https://doi.org/10.1016/j.anifeedsci.2018.05.006

**Kasuya, M. C. M., da Luz, J. M. R., da Silva Pereira, L. P., da Silva, J. S., Cuquetto, H., & Teixeira, M.** 2012. Growth inhibition of pathogenic root fungi by extracts of ectomycorrhizal fungi or *Picea glehnii* inoculated with ectomycorrhizal fungi. *BIOTROPIA*, 9, 53–61. https://doi.org/10.11598/btb.1996.0.9.125

**Kellogg, T.F.** 1974. Steroid balance and tissue cholesterol accumulation in germfree and conventional rats fed diets containing saturated and polyunsaturated fats. *Journal of Lipid Research*, 15(6): 574–579. https://doi.org/10.1016/S0022-2275(20)36758-4

**Koné, G.A., Good, M. & Kouba, M.** 2020. Performance of guinea fowl fed hevea seed meal or cashew nut meal as a partial substitute for soya bean meal. *Animal*, 14(1): 206–214. https://doi.org/10.1017/S175173111900185X

**Koné, G.A., Good, M., Tiho, T., Ngatta, Z.R., Grongnet, J.-F. & Kouba, M.** 2022. Sensory characteristics and consumer preference for meat from guinea fowl fed hevea seed meal or cashew nut meal supplemented diets. *Poultry Science*, 101(12): 102212. https://doi.org/10.1016/j.psj.2022.102212

**Kouakou, N.D.V., Angbo-Kouakou, C.E.M., Koné, G.A., Kouame, K.B., Yéboué, F.D.P. & Kouba, M.** 2018. Valorisation des tourteaux d'amandes d'hévéa et d'anacarde chez le porc en postsevrage et en croissance. *Revue d'élevage et de médecine vétérinaire des pays tropicaux*, 71(1–2): 81–85. https://doi.org/10.19182/remvt.31256

**Kouakou, N.D.V., Coulibaly, S.B.M., Angbo-Kouakou, C.E.M., Thys, E., Assidjo, N.E. & Kouba, M.** 2016. Réduction des coûts alimentaires des lapins (*Oryctolagus cuniculus* L.) par la distribution de l'herbe de lait (*Euphorbia heterophylla* (L.) Klotz. & Garcke) associée à l'herbe de Guinée (*Panicum maximum* Jacq.) Lam... *Journal of Applied Biosciences*, 99, 9373–9381. https://doi.org/10.4314/jab.v99i1.3

**Kouakou, N.D.V., Grongnet, J.-F., Assidjo, N.E., Thys, E., Marnet, P.-G., Catheline, D., Legrand, P. & Kouba, M.** 2013. Effect of a supplementation of *Euphorbia heterophylla* on nutritional meat quality of Guinea pig (*Cavia porcellus* L.). *Meat Science*, 93(4): 821–826. https://doi.org/10.1016/j.meatsci.2012.11.036

**Kouassi, G.F., Koné, G.A., Good, M., Assidjo, N.E. & Kouba, M.** 2020. Effect of *Hevea brasiliensis* seed meal or *Euphorbia heterophylla* seed supplemented diets on performance, physicochemical and sensory properties of eggs, and egg yolk fatty acid profile in guinea fowl (*Numida meleagris*). *Poultry Science*, 99(1): 342–349. https://doi.org/10.3382/ps/pez500

**Kühnel, S., Schols, H.A. & Gruppen, H.** 2011. Aiming for the complete utilization of sugar-beet pulp: Examination of the effects of mild acid and hydrothermal pretreatment followed by enzymatic digestion. *Biotechnology for Biofuel*s, 4(1): 14. https://doi.org/10.1186/1754-6834-4-14

**Lans, C., Harper, T., Georges, K. & Bridgewater, E.** 2000. Medicinal plants used for dogs in Trinidad and Tobago. *Preventive Veterinary Medicine*, 45(3–4): 201–220. https://doi.org/10.1016/S0167-5877(00)00123-9

**Le Goff, G. & Noblet, J.** 2001. Comparative total tract digestibility of dietary energy and nutrients in growing pigs and adult sows. *Journal of Animal Science*, 79(9): 2418–2427. https://doi.org/10.2527/2001.7992418x

**Lima, P. de Mello Tavares, Oliveira, P. Batelli, Campeche, A., Moreira, G. Dias, Paim, T. do Prado, McManus, C., Abdalla, A.L., Dantas, A.M. Morais, De Souza, J. Rodrigues & Louvandini, H.** 2014. Methane emission of Santa Inês sheep fed cottonseed by-products containing different levels of gossypol. *Tropical Animal Health and Production*, 46(1): 285–288. https://doi.org/10.1007/s11250-013-0491-3

**Linden, J.** 2012. Jatropha as a new livestock feed resource. In: *The Poultry Site*. [Cited 30 June 2025]. https://www.thepoultrysite.com/articles/jatropha-as-a-new-livestock-feed-resource

**Liu, J., Zhao, L., Zhao, Z., Wu, Y., Cao, J., Cai, H., Yang, P. & Wen, Z.** 2022. Rubber (*Hevea brasiliensis*) seed oil supplementation attenuates immunological stress and inflammatory response in lipopolysaccharide-challenged laying hens. *Poultry Science*, 101(9): 102040. https://doi.org/10.1016/j.psj.2022.102040

**Londero, A., León Peláez, M.A., Diosma, G., De Antoni, G.L., Abraham, A.G. & Garrote, G.L.** 2014. Fermented whey as poultry feed additive to prevent fungal contamination. *Journal of the Science of Food and Agriculture*, 94(15): 3189–3194. https://doi.org/10.1002/jsfa.6669

**Lupo, C.R., Grecco, F.C. de Almeida Rego, Eleodoro, J.I., Cunha Filho, L.F. Coelho, Serafim, C.C., Dos Santos, J. Sifuentes, Ludovico, A., De Almeida, M. Ferreira, Zundt, M., Garrido, J. Volpato & Hernandes, C.** 2019. Viability of the use of bovine milk whey at lamb finishing: Performance, carcass, and meat parameters. *Journal of Applied Animal Research*, 47(1): 449–453. https://doi.org/10.1080/09712119.2019.1653302

**Madubuike, F.N., Ekenyem, B.U. & Obih, T.K.O.** 2006. Performance and cost evaluation of substituting rubber seed cake for groundnut cake in diets of growing pigs. *Pakistan Journal of Nutrition*, 5(1): 59–61. https://doi.org/10.3923/pjn.2006.59.61

**Manzanares, P., Ruiz, E., Ballesteros, M., Negro, M.J., Gallego, F.J., López-Linares, J.C. & Castro, E.** 2017. Residual biomass potential in olive tree cultivation and olive oil industry in Spain: Valorization proposal in a biorefinery context. *Spanish Journal of Agricultural Research*, 15(3): e0206. https://doi.org/10.5424/sjar/2017153-10868

**Mayer, M., Vogl, C.R., Amorena, M., Hamburger, M. & Walkenhorst, M.** 2014. Treatment of organic livestock with medicinal plants: A systematic review of European ethnoveterinary research. *Complementary Medicine Research*, 21(6): 375–386. https://doi.org/10.1159/000370216

**Menzies, C.R. ed.** 2006. *Traditional ecological knowledge and natural resource management*. 274 pp. Lincoln, USA, University of Nebraska Press.

**Mills, S., Ross, R.P., Hill, C., Fitzgerald, G.F. & Stanton, C.** 2011. Milk intelligence: Mining milk for bioactive substances associated with human health. *International Dairy Journal*, 21(6): 377–401. https://doi.org/10.1016/j.idairyj.2010.12.011

**Modesti, C. de Fátima, Corrêa, A. Duarte, Oliveira, E. Domingos de, Abreu, C.M. Patto de & Santos, C. Donizete dos.** 2007. Caracterização de concentrado protéico de folhas de mandioca obtido por precipitação com calor e ácido. *Ciência e Tecnologia de Alimentos*, 27(3): 464–469. https://doi.org/10.1590/S0101-20612007000300007

**Navarro, S.L.B. & Rodrigues, C.E.C.** 2016. Macadamia oil extraction methods and uses for the defatted meal byproduct. *Trends in Food Science & Technology*, 54, 148–154. https://doi.org/10.1016/j.tifs.2016.04.001

**Nega, T. & Woldes, Y.** 2018. Review on nutritional limitations and opportunities of using rapeseed meal and other rape seed by-products in animal feeding. *Journal of Nutritional Health & Food Engineering*, 8(1): 43–48. https://doi.org/10.15406/jnhfe.2018.08.00254

**Noblet, J. & Perez, J.M.** 1993. Prediction of digestibility of nutrients and energy values of pig diets from chemical analysis. *Journal of Animal Science*, 71(12): 3389–3398. https://doi.org/10.2527/1993.71123389x

**NRC (National Research Council).** 2001. *Nutrient requirements of dairy cattle*. Washington, DC., National Academies Press. https://doi.org/10.17226/9825

**Nwokolo, E. & Smartt, J., eds.** 1996. *Food and feed from legumes and oilseeds*. 1st ed. London, Chapman & Hall.

Nwokoro, S.O, Vaikosen, S.E. & Bamgbose, A.M. 2005. Nutrient composition of cassava offals and cassava sievates collected from locations in Edo State, Nigeria. *Pakistan Journal of Nutrition*, 4(4): 262–264. https://doi.org/10.3923/pjn.2005.262.264

**Odunsi, A.A. & Oyewole, S.** 1996. Response of broiler chicks to diets containing varying levels of cashew nut oil and palm oil. *Ghana Journal of Agricultural Science*, 29(2): 59–64. https://doi.org/10.4314/gjas.v29i2.1991

**Ogueji, E.O., Iheanacho, S.C., Mbah, C.E., Yaji, A.J. & Ezemagu, U.** 2020. Effect of partial and complete replacement of soybean with discarded cashew nut (*Anacardium occidentale* L.) on liver and stomach histology of *Clarias gariepinus* (Burchell, 1822). *Aquaculture and Fisheries*, 5(2): 86–91. https://doi.org/10.1016/j.aaf.2019.10.005

**Okike, I., Samireddypalle, A., Kaptoge, L., Fauquet, C., Atehnkeng, J., Bandyopadhyay, R., Kulakow, K., Duncan, A., Alabi, T. & Blummel, M.** 2015. Technical innovations for small-scale producers and households to process wet cassava peels into high quality animal feed ingredients and aflasafe™ substrate. *Food Chain*, 5(1): 71–90. https://doi.org/10.3362/2046-1887.2015.005

**OSTP (Office of Science and Technology Policy).** 2022. White House releases first-of-a-kind Indigenous knowledge guidance for federal agencies. In: *The White House*. Washington, DC.. [Cited 30 June 2025]. https://www.whitehouse.gov/ostp/

**Palmonari, A., Cavallini, D., Sniffen, C.J., Fernandes, L., Holder, P., Fagioli, L., Fusaro, I., Biagi, G., Formigoni, A. & Mammi, L. 2020.** Short communication: Characterization of molasses chemical composition. *Journal of Dairy Science*, 103(7): 6244–6249. https://doi.org/10.3168/jds.2019-17644

**Pavlista, A.D. & Rush, I.G.** 2002. *EC02-152 – S value of potatoes for feeding livestock*. Extension circular No. 4764. University of Nebraska–Lincoln Extension. https://digitalcommons.unl.edu/extensionhist/4764

**Pfaltzgraff, L.A., De Bruyn, M., Cooper, E.C., Budarin, V. & Clark, J.H.** 2013. Food waste biomass: A resource for high-value chemicals. *Green Chemistry*, 15(2): 307. https://doi.org/10.1039/c2gc36978h

**Rajaguru, A.S.B. & Ravindran, V.** 1979. Rubber seed meal as a protein supplement in growing swine rations. *Journal of the National Science Foundation of Sri Lanka*, 7(2): 101–104. https://jnsfsl.sljol.info/articles/10994

**Rapetti, L., Falaschi, U., Lodi, R., Vezzoli, F., Tamburini, A., Greppi, G.F. & Enne, G.** 1995. The effect of liquid whey fed to dairy goats on milk yield and quality. *Small Ruminant Research*, 16(3): 215–220. https://doi.org/10.1016/0921-4488(95)00637-Z

**Ravindran, V., Kornegay, E.T. & Rajaguru, A.S.B.** 1987. Influence of processing methods and storage time on the cyanide potential of cassava leaf meal. *Animal Feed Science and Technology*, 17(4): 227–234. https://doi.org/10.1016/0377-8401(87)90054-X

**Rémond, B. & Coulon, J.B.** 1986. Digestion du lactosérum dans le rumen chez les vaches laitières. *Reproduction Nutrition Development*, 26(1B): 311–312. https://doi.org/10.1051/rnd:19860232

**Riaz, T., Iqbal, M.W., Mahmood, S., Yasmin, I., Leghari, A.A., Rehman, A., Mushtaq, A., Ali, K., Azam, M. & Bilal, M.** 2023. Cottonseed oil: A review of extraction techniques, physicochemical, functional, and nutritional properties. *Critical Reviews in Food Science and Nutrition*, 63(9): 1219–1237. https://doi.org/10.1080/10408398.2021.1963206

**Sánchez, C. J., Barrero-Domínguez, B., Martínez-Miró, S., Madrid, J., Baños, A., Aguinaga, M. A., López, S. & Hernández, F.** 2022. Use of olive pulp for gestating Iberian sow feeding: Influence on performance, health status indicators, and fecal microbiota. *Animals*, 12(22): 3178. https://doi.org/10.3390/ani12223178

**Santana-Méridas, O., González-Coloma, A. & Sánchez-Vioque, R.** 2012. Agricultural residues as a source of bioactive natural products. *Phytochemistry Reviews*, 11(4): 447–466. https://doi.org/10.1007/s11101-012-9266-0

**Schingoethe, D.J. & Beardsley, G.L.** 1975. Feeding value of corn silage containing added urea and dried whey. *Journal of Dairy Science*, 58(2): 196–201. https://doi.org/10.3168/jds.S0022-0302(75)84544-9

**Schingoethe, D.J. & Skyberg, E.W.** 1981. Lactation and growth of dairy cows and steers from large amounts of dried whey. *Journal of Dairy Science*, 64(7): 1571–1578. https://doi.org/10.3168/jds.S0022-0302(81)82727-0

**Shittu, T.A., Alimi, B.A., Wahab, B., Sanni, L.O. & Abass, A.B.** 2016. Cassava flour and starch: Processing technology and utilization. In: H.K. Sharma, N.Y. Njintang, R.S. Singhal & P. Kaushal, eds. *Tropical Roots and Tubers*, pp. 415–450. Hoboken, USA, Wiley. https://doi.org/10.1002/9781118992739.ch10a

**Sniffen, C.J., O'Connor, J.D., Van Soest, P.J., Fox, D.G. & Russell, J.B.** 1992. A net carbohydrate and protein system for evaluating cattle diets: II. Carbohydrate and protein availability. *Journal of Animal Science*, 70(11): 3562–3577. https://doi.org/10.2527/1992.70113562x

**Spek, J.-W. & Blok, M.-C., eds.** 2018. *CVB feed table 2018: Chemical composition and nutritive values of feedstuffs* The Hague, Kingdom of the Netherlands, FND (Federatie Nederlandse Diervoederketen [Dutch Feed Chain Federation]). https://appec-h.com/wp-content/uploads/2024/08/CVB-Feed-Table-2018_Chemical-composition-and-nutritional-values-of-feedstuffs.pdf

**Terramoccia, S., Bartocci, S., Taticchi, A., Di Giovanni, S., Pauselli, M., Mourvaki, E., Urbani, S. & Servili, M.** 2013. Use of dried stoned olive pomace in the feeding of lactating buffaloes: Effect on the quantity and quality of the milk produced. *Asian-Australasian Journal of Animal Sciences*, 26(7): 971–980. https://doi.org/10.5713/ajas.2012.12627

**Thivend, P.** 1977. Use of whey in feeding ruminants: With particular reference to pollution problems. FAO Animal Production and Health Paper No. 10. Rome, FAO. [Cited 30 June 2025]. https://www.fao.org/3/x6512e/X6512E09.htm.

**Tzamaloukas, O., Neofytou, M.C. & Simitzis, P.E.** 2021. Application of olive by-products in livestock with emphasis on small ruminants: Implications on rumen function, growth performance, milk and meat quality. *Animals*, 11(2): 531. https://doi.org/10.3390/ani11020531

**Ukachukwu, S.N.** 2005. Studies on the nutritive value of composite cassava pellets for poultry: Chemical composition and metabolizable energy. *Livestock Research for Rural Development*, 17(11). http://www.lrrd.org/lrrd17/11/ukac17125.htm

Livestock play a central role in a circular bioeconomy by converting non-edible biomass into high-value animal-sourced foods, organic fertilizers and renewable energy. By recycling nutrients and closing cycles, they contribute to sustainable agriculture and global food security. By combining technical insights with concrete examples, the guideline offers policymakers, researchers and practitioners tools to design and implement more sustainable livestock systems within a circular bioeconomy framework.

This technical guideline was developed by a Technical Advisory Group of experts in livestock production, nutrition and circular systems, representing diverse regions and stakeholders, and underwent an extensive public review. It presents the contribution of livestock to reducing food–feed competition, enhancing soil health and supporting bio-based industries. Beyond food, animal by-products are valorized into pharmaceuticals, cosmetics and bioenergy, while manure-based biogas provides renewable energy and mitigates greenhouse gas emissions. Together, these functions demonstrate the multiple pathways through which livestock strengthen circular bioeconomy systems.

The guideline also provides an overview of commonly used metrics and indicators to assess environmental impacts in livestock production within a circular bioeconomy, highlighting both their strengths and limitations. It examines the use of plant- and animal-based by-products for feed, as well as the valorization of manure and other residuals. Regional case studies illustrate practical recovery strategies and innovations that improve efficiency and sustainability. The document further explores political and regulatory implications of circular bioeconomy policies, their effectiveness in supporting by-product utilization and the challenges that remain.

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