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Review

# Biorefinery development in livestock production systems: Applications, challenges, and future research directions

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ABSTRACT

Sustainable development and reducing natural and energy resource consumption are the focus of the policies of many institutions. In this context, livestock farming is one of the major anthropogenic sources of GHG and acidifying gas emissions and requires comprehensive analysis to minimise its ecological footprint. For this reason, it is beneficial to analyse the various processes within this production sector to reduce the consumption of resources, particularly water and soil consumption; reduce energy consumption; and try to valorise the biowaste produced, especially manure, byproducts and wastewater. Reusing residual bioresource and organic waste offers the possibility of valorising a discarded product and, at the same time, reducing the consumption of natural resources. For this purpose, biorefinery processes allow bioresources to be transformed into bioproducts or bioenergy. Therefore, this study investigates the application of biorefinery processes to animal-derived waste, aiming to extract valuable resources while curbing resource consumption. This review analysed 293 scientific papers on biorefinery processes published in the last 11 years applied to livestock biomass to extract relevant information to understand the evolution of this topic and formulate hypotheses regarding future research directions. The analysis strongly emphasizes energy production and a growing interest in insect cultivation. In the coming years, one of the most significant challenges will be the successful transfer of technologies and processes from experimental research to the applied industry. To do this, it will be necessary to reduce costs, exploit economies of scale, improve process management, and develop synergies between different industrial sectors to implement smart circular economy systems. Overall, this review aims to clarify the hypothesis driving research in this area and emphasizes the tangible applications of findings within the broader context of sustainable resource management.

## 1. Introduction

The social importance of livestock farming goes far beyond job creation: many European cultural landscapes and traditions have developed alongside livestock production (Herrero et al., 2013). It is an essential part of the economy and culture of many regions, including many marginal areas in rural areas of Arava (Israel), Murcia (Spain), La Vallée de la Drôme (France), Salzburg region (Austria) and Tuscany (Italy) (de Roest et al., 2018). The importance of this sector for the economy and the environmental, industrial and energy policies of the European Union (EU) and its member states is evidenced by the high number of animal units achieved (142 million pigs, 76 million bovine animals, 60 million sheep and 11 million goats in December 2021) (Scarlat et al., 2018b; Eurostat, 2022).

From a circular bioeconomy perspective, livestock farming has many other important roles: *i)* contributing to more efficient agriculture through the exploitation and valorisation of byproducts in the food chain, recycling inedible biomass and deriving new sources of protein for animals (Farias et al., 2020); regulating ecological cycles, closing nutrient cycles, and increasing soil fertility and carbon sequestration through recycling and utilisation of manure as a bioresource in combination with fodder (Chiumenti et al., 2019; Hilimire, 2011); *ii)*

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providing feedstock for renewable energy production and thus contributing to the transition to renewable energy and byproduct production for the industrial sector (e.g., for animal feed, cosmetics, textiles, pharmaceutical industry) (Economics and Library, 2010; Ferrari et al., 2022); and *iii)* providing ecosystem services essential for the vitality of territories, rural employment, landscape conservation, biodiversity, and cultural heritage (Dumont et al., 2019; Rodríguez-Ortega et al., 2014). In addition, it is possible to use the effluent produced by farmed animals to produce biogas, biomethane, and electricity; thus it is possible to turn a waste into an alternative energy source (Scarlat et al., 2018a).

However, livestock farming also has negative impacts on the environment due to the consumption of limited resources (land, water, and energy) (Ferrari et al., 2021b) and the production of flows of nutrients, greenhouse gases, toxic substances, etc., which can affect biodiversity, human health, and ultimately the functionality of ecosystems on which communities depend for food production (Peyraud and MacLeod, 2020). Livestock farming contributes to climate change by emitting greenhouse gases, both directly (e.g., through enteric fermentation) and indirectly (e.g., through feed production activities and deforestation). According to FAO results, livestock activities were responsible for the emission of 8.1 Gt $CO_2$eq in the world and 0.25 Gt $CO_2$eq in Europe (10% of total emissions in EU-28) in 2017 (Peyraud and MacLeod, 2020); these gases consist mostly of methane (50%), nitrous oxide ($N_2O$) (24%) and carbon dioxide ($CO_2$) (26%) (Steinfeld et al., 2007). Analysing by species, cattle are the most significant contributors (37.0% beef, 19.8% dairy cattle), followed by pigs (10.1%) and poultry (9.8%) (Peyraud and MacLeod, 2020). Moreover, the high numbers of animal units have often been associated with soil pollution due to the disposal of nitrogen in sewage (Ferrari et al., 2021a).

In recent years, the EU and its member states have issued various regulations, directives and laws concerning livestock farming and biomass management (Directive 2001/81/EC, 2001; European Commission, 1991). These regulations were studied by Velthof et al. (2015), who reviewed the nitrogen excretion factors applied to a number of animal categories in policy reports from different EU member states. This work has also been done by other authors over the years, the results were also very different from each other, this is because of the different type of breeding and environmental conditions (Bao et al., 2019). Additionally, Wieruszewski and Mydlarz (2022) discussed the information gathered on biomass energy to achieve EU energy targets. The regulatory system for biorefineries in Europe is extensive. In some cases, these are documents specifically dedicated to this topic; more often, they are included in more comprehensive measures concerning sustainable development and energy transition.

One of the earliest EU acts was the Council Directive 91/676/EEC concerning the protection of water against pollution caused by nitrates from agricultural sources: the "Nitrates Directive" (European Commission, 1991). The directive prescribes the determination of water bodies vulnerable to nitrate pollution and their water catchment areas. The directive states that the amount of nitrogen that may be introduced into soils in these areas may not exceed 170 kg/ha/year. The European legislation requires that alternative solutions for the treatment of livestock manure must be adopted to comply with these limits. These solutions do not exclude the use of manure as fertiliser but involve more elaboration that could be facilitated by energy production, as in the case of biorefineries. In fact, these processes also allow alternative products, such as bioproducts and bioenergy, to be obtained.

The International Energy Agency Bioenergy Task 42 provided the definition of biorefinery: "the sustainable processing of biomass into a spectrum of biobased products (food, feed, chemicals, materials) and bioenergy (biofuels, power and/or heat)" (International Energy Agency - Bioenergy Task 42, 2019). Using biomass as a raw material can provide a benefit by reducing the environmental impact and greenhouse gas emissions for producing bioproducts (Bajpai, 2013). Biorefineries can be classified according to four characteristics (Cherubini et al., 2009):

- Platform. These are the intermediate products between the raw materials and the final bioproducts. The most important are biogas, syngas, hydrogen, carbohydrates, lignin, and oils.
- Bioproducts. These are the final products and can be of two types: energy (electricity, heat) or materials (for different types of industry).
- Raw materials. They can be dedicated biomass (energy crops, forest products) or waste and byproducts (including livestock manure).
- Type of process used. They can be of different types, even in combination: thermal, chemical, mechanical, and biological.

In this research, the previous classification was used, indicating "Platform" with "bioproduct produced", "Bioproducts" with "Destination of bioproduct", and "Raw materials" with "Biomass used".

Biorefineries contribute to a more sustainable industrial system by preserving resources and reducing greenhouse gas emissions (Rekleitis et al., 2020). Nevertheless, the production of biomaterials entails other types of environmental impacts: land use, water eutrophication, and high energy demand (Biswal et al., 2020). To assess these impacts, an essential tool is life cycle assessment (LCA), which evaluates the environmental impact of a product or process from raw material to end-of-life disposal (Jacquemin et al., 2012). A certain number of LCAs have been published to analyse the environmental impact of biorefineries in comparison with traditional production systems; in addition, many technoeconomic analyses have been published concerning the processes and biomasses involved. This large amount of published research has produced numerous results, necessitating the publication of specific review articles on a particular treatment adopted, a specific biomass used or a certain bioproduct obtained. At this point, it is necessary to understand how the various topics, products and techniques integrate and how the authors decided to deal with them: technical articles, review articles, LCA. For this reason, a systematic review of the literature on this topic is necessary.

This paper proposes a systematic review of articles published over the past 11 years concerning biorefineries applied to byproducts and waste from livestock farming. A large set of articles has been examined in an attempt to extract the essential information on the applied biorefinery processes at different scales (laboratory, pilot and full scale), the most successful pretreatments used, and the possible biorefinery outputs. A special focus was devoted to reviews, LCAs and techno-economic assessments to better define the directions of scientific research, technical applications, and the environmental consequences of these processes. Through this holistic approach, this research aims to take a detailed look at the biomass used in refinery processes and, through the systematic analysis of these data, interpret the research trend over the years, provide key elements for understanding this phenomenon for political decision-makers and propose new routes for research.

## 2. Field of analysis and research methodology

The methodology applied in this research consists of three stages. First is the definition of the analysis field, with the fundamental concepts for the search. Second, the search string on Scopus was described, and articles were identified. Third, relevant information was extracted from the selected articles and their analysis and discussion.

This study analysed research on biorefineries applied to the livestock sector, with a particular interest in managing and valorising manure and wastewater. Based on the objectives of the research, two key concepts were established and were used to define the search string on the Scopus database (Fig. 1): (i) biorefinery, regarding the way biomass is managed, and (ii) animal and livestock, regarding the scope of application. The two concepts were converted into two sets of search terms for the articles. Concerning the first concept, the search focused on the works the relevant authors considered related to the biorefinery, defined as a series of organised processes for biomass valorisation. The string used for the research was *(biorefinery or biorefineries or biorefining or biorefiner*) and*

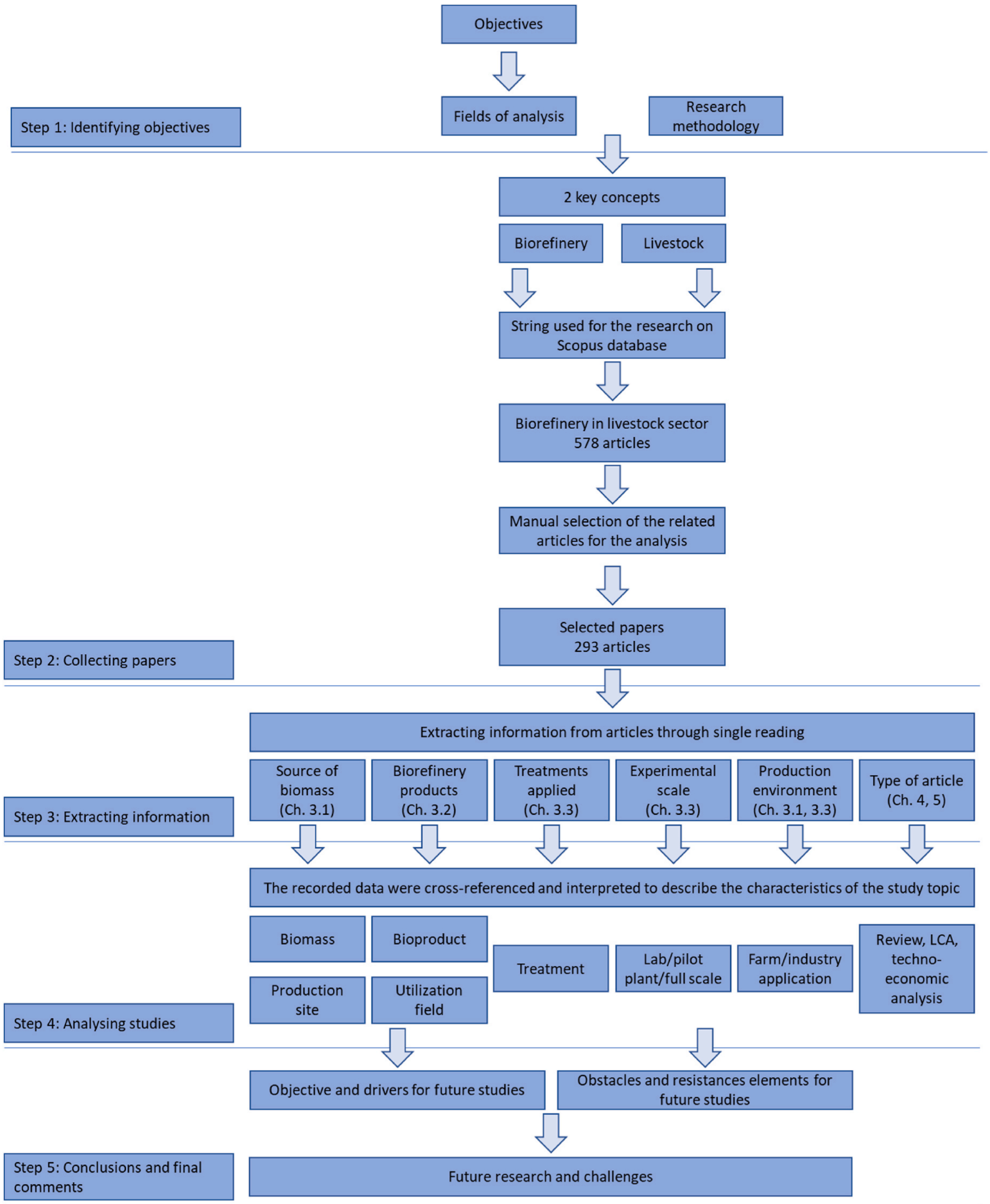


**Fig. 1.** Flowchart of the methodology used in this systematic review.

*(fish or aquaculture or insect or goat or sheep or livestock or cattle or pigs or poultry or swine or cow or dairy or beef or manure or slurry)*. This string was applied through the title-abstracts-keywords indexed by the Scopus database, as it collects most scientific publications. This also allows for the search to be refined using a series of filters, particularly articles from 2012 to the present, in English, and only articles, reviews and conference papers were selected. This choice made it possible to include many articles to establish a more complete framework of the topic. The downside of this choice was that on examining the articles individually, many (almost half) were found to be unrelated to the topic and therefore not useable; this was because, in the abstract, the words of the research string were randomly present, but the actual topic was different from the targeted research areas.

The search produced 578 articles published between 2012 and 2022. The articles were analysed individually and filtered to select only those relevant to the research. Among the articles that contained search terms, only those that applied biorefinery processes to livestock biomass or produced livestock-specific products with such processes, e.g., feed or supplements, were included.

The following exclusion criteria were used:

Articles that mentioned biorefinery only incidentally, without it being the subject of the article.

Articles that mentioned livestock breeding or certain animal species incidentally, without them being the subject of the study.

Conference articles with the same author and topic as a scientific article were included. In this case, the conference article was considered a duplicate.

The first categorisation of articles was based on the origin of the biomass (Section 3.1). Articles were categorised according to the production site: agro-livestock farm, industry, or civil/urban area. Although the main focus of this article was biomass from livestock farming, the study was completed with the analysis of articles in which livestock farming was the destination of biorefinery activities. For biomass from livestock farming, the animals bred were also detailed to discuss the most common and important productions. Once the sectors of biomass production had been determined, the different types of biomass were described. Biomass was divided into manure, byproducts, main products, waste, and other specific types. These categorisations allowed for analysing the time course of scientific production by discriminating between the various sectors; it also made it possible to produce a series of considerations regarding the interactions between the biomass used and the processes implemented.

Once the origin and nature of the biomass used had been described, the analysis focused on the bioproducts obtained (Section 3.2). The first classification made it possible to describe the nature of the byproducts obtained; the main categories identified were biogas, biomethane, biofuels, bioethanol, bioplastics, microalgae, nutrients (fats, carbohydrates and proteins), fertilisers, and purified water. In addition to the total article count, the analysis made it possible to describe the temporal trends of the bioproducts obtained; this is useful information for hypothesising future biorefinery scenarios and trends. The categorisation of the nature of the bioproducts made it possible to define the production sectors for which the biorefinery processes are intended. A number of key destinations of use were also identified for this categorisation: animal feed, energy, fertilisers, pharmaceutical industry, chemical industry, manufacturing, and purified water. The description of the biomass of origin and the final bioproducts preceded the study of the processes used. The two pieces of information were then cross-referenced to determine which processes are most frequently associated with each type of biomass/bioproduct.

For research purposes, the analysed articles were classified according to the biorefinery process used and the production context in which the process occurred (Section 3.3). The biorefinery processes were grouped into the following categories: thermal, chemical, mechanical, biological, and anaerobic digestion. It was also recognised whether these processes took place in the laboratory, in pilot plants or on a full scale and whether the production context was agro-livestock farms or other industries.

## 3. Results

After filtering, the literature search identified 293 studies based on inclusion and exclusion criteria.

### 3.1. Sources of biomass

To describe the state of the art of biorefineries, it is essential to carefully consider the biomass used.

In this review, 214 articles were analysed that utilise biomass from livestock (cattle, pigs, poultry, other animals), insects, aquaculture, and processing plants for products derived from these animals. The remaining articles consider other biomasses, whether agricultural, civil, or industrial. For a better understanding of the information, in Fig. 2, the categories are grouped according to the area of origin of the biomass: "farm" for biomass produced directly in classic agro-livestock farms, "industry" if the biomass is produced in livestock production transformation processes, and "other" for particular livestock production activities. In scientific research, the most significant biomass contribution is cattle farming, with 86 articles, 29.4% of the total; pigs and poultry, both with 56 articles, 19.1%. The contribution of other animals, horses, sheep, etc., is much lower, 4 articles, or 1.4% of studies; this is due to the lower diffusion of these farms and to the smaller amount of biomass, mainly manure, that can be collected. The importance of cattle, pigs, and poultry is not limited to the livestock sector but also involves the processing industries. Of these, the most important is undoubtedly the dairy industry, which is mentioned as the source of biomass in 25 scientific contributions, corresponding to 8.5% of the total. The organic content of wastewater and waste from this industry makes these biomasses particularly suitable for biorefineries. A promising area in the next few years will be the breeding and utilisation of insects (Chapter 6). These can be used to process waste and other biomass and, above all, as a primary source of protein and other nutrients. These products are used to produce food for animals and, in the future, for humans. This analysis showed 20 articles, 6.8% of the total, in which insects were bred for biomass production.

Among the non-livestock biomasses, the most common in this analysis were agricultural byproducts (straw, cornstalk, pruning residues), with 100 papers, 34.1% of the total (Fig. 3). This biomass is very often used in combination with other biomasses, especially those from animal farming. It is mainly used for energy purposes or the production of animal feed. Biomass from industry and settlements is less used: 29 articles for food waste, 9.9%; 18 articles for civil and industrial waste, 6.1%; and 13 papers for wastewater, 4.4%. Due to their characteristics, these biomasses often have to be treated differently from byproducts and

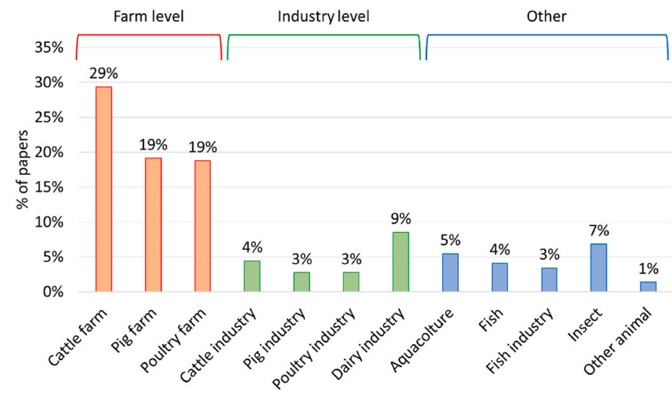


**Fig. 2.** Number of papers per origin of bioresources used (animal sector).

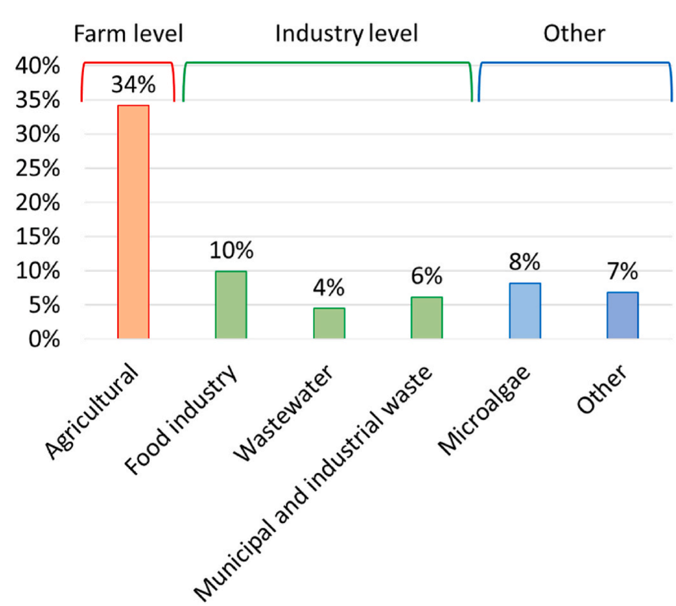


**Fig. 3.** Number of papers per origin of bioresources used (other sectors).

manure, so using them in combination is not always possible.

An interesting topic is microalgae; they are either used as biomass treatment, e.g., for removing nutrients or harmful substances, or cultivated to produce biomass for protein, oils or carbohydrates. This analysis found 24 articles dealing with this topic, 8.2% of the total number of articles. A more specific search can verify the increase in research interest in this area; the number of articles published on this topic in the biorefinery field rose from 23 papers in 2012 to 268 papers in 2022.

Once the areas of origin of biomass have been examined, the nature of the biomass itself can be analysed (Table 1, Fig. 4). In Table 1, in addition to the type of biomass, the environment of use, i.e., where the biorefinery process takes place is also shown. The biorefinery can occur on the agro-livestock farm, usually the same one where the biomass was produced, or in dedicated industries, where the biomass is transported and processed.

In this analysis, most articles use animal manure, with 123 articles, 25.8%. However, manure is not the only livestock biomass used: 10 articles used rumen, and 1 used urine. In addition, many articles refer to poultry litter.

From the agro-forestry sector, 80 articles (16.8%) on agricultural byproducts and 95 articles (19.9%) on agricultural and forestry biomass were identified in this analysis. In the first group, biomasses that do not constitute the main product of cultivation were included, e.g., straw, clippings, and harvest residues. The energy crops fall within the second group, namely, woody biomass harvested for the biorefinery and hay and grass used as fodder.

Digestate was among the products used in 7 articles (1.5%). This result, although low compared to the others, shows the importance of this product, not only as a natural byproduct of anaerobic digestion but also as a primary product for other types of biorefineries.

Among the non-agricultural biomasses, the dairy industry's importance is demonstrated by the explicit interest in whey as biomass for biorefinery applications, as demonstrated in 10 articles (2.1%). This biomass is primarily used for energy production. However, there is no shortage of other applications, such as the pharmaceutical, animal feed, and manufacturing industries.

The advantages of the combined use of biomass have been confirmed in numerous papers. This study analysed biomass matrices that included animal manure to observe which biomasses were most often combined with it.

The biomass most frequently used combined with manure is agricultural waste and biomass, with 44 articles with both biomasses (Fig. 5). This combination is also particularly frequent because it is the most typical for anaerobic digestion in agriculture. In agro-livestock farms, it is common to use the two matrices in combination to supply the digester. Another 15 articles combined biomass from livestock farms with biomass from animal processing industries. In some cases, they are techno-economic or LCA articles in which all biomass from a particular sector, farm animals in this case, is included. A lesser weight in this analysis is found for wastewater (13 articles), biomass from the food industry (12 articles) and civil and industrial waste (11 articles), probably due to their different origins than manure.

**Table 1**
Number of articles per type of biomass used. The total is higher than the number of articles because more than one biomass is used in many pieces of research.

| Origin | Biomass | Number of articles and percentage (%) | Farm | Industry | Other |
|---|---|---|---|---|---|
| Agriculture | Manure | 123 (42.0%) | 57 | 62 | 17 |
| | Agricultural byproduct | 80 (27.3%) | 29 | 48 | 15 |
| | Agricultural and forestry biomass | 95 (32.4%) | 40 | 41 | 20 |
| Industry | Whey | 10 (3.4%) | 0 | 10 | 0 |
| | Industrial or urban waste | 82 (28.0%) | 13 | 69 | 6 |
| | Microalgae | 18 (6.1%) | 2 | 12 | 3 |
| | Digestate | 7 (2.4%) | 3 | 6 | 0 |
| | Other | 16 (5.5%) | 5 | 11 | 1 |

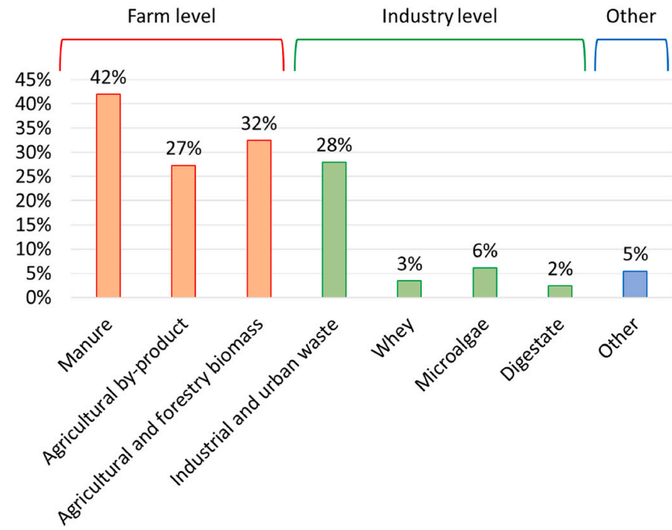


**Fig. 4.** Number of articles per type of biomass used (see also Table 1).

### 3.2. Biorefinery products

Once the biomasses were described, information about the bioproducts produced in the biorefinery process was extracted (Fig. 6). These confirm the analyses carried out earlier concerning the biomasses of origin and the types of treatments used.

Most of the processes are aimed at biogas production (70 articles, 23.9% of the total); in fact, anaerobic digestion is the most commonly used process. Closely related to biogas is the production of biomethane, which is examined in 13 articles, 4.4% of the total. In this analysis, the distinction between the two categories is based on what the author of the article identifies as the objective of their paper. Nevertheless, in bioenergy, two products have the same number of articles: ethanol and biodiesel (and biofuels); 22 articles. The first is used as an energy source and an animal feed additive. The topic of biofuels is currently crucial, and the increasing research trend confirms the interest of researchers in this topic (Fig. 7). The same applies to ethanol; this trend demonstrates the increased interest in this production. Lower values, but still worth considering, are reported for biohydrogen in 7 articles and heat in 6 articles.

In addition to bioenergy, the other crucial area for byproducts is nutrients. Data on protein are notably interesting; this production is the topic in 54 articles. In many cases, it is the production of animal feed or supplements made from agricultural products or byproducts; in many other cases, the origin of the biomass from which the proteins are produced is insects, a sector that is overgrowing. In all cases, these articles focus their analysis on the sustainability of the livestock production chain. Indeed, reducing the energy, water and soil used for food production is a growing problem. Volatile fatty acids and carbohydrates were essential in 40 and 27 articles, respectively.

The production of fertiliser is significant, with 21 articles. This product is produced by anaerobic digestion in the form of digestate. However, in the articles cited in the count above, the reference to fertiliser by the research authors is explicit. This demonstrates the direct interest in this product and shows that it is not just a byproduct but constitutes the actual target of the study.

Some products are not considered in the analysis because they are irrelevant to the overall theme, not sufficiently specified by the authors (e.g., in some papers, generic bioenergy production is mentioned), or present with insufficient citations. Regarding the total of bioproducts

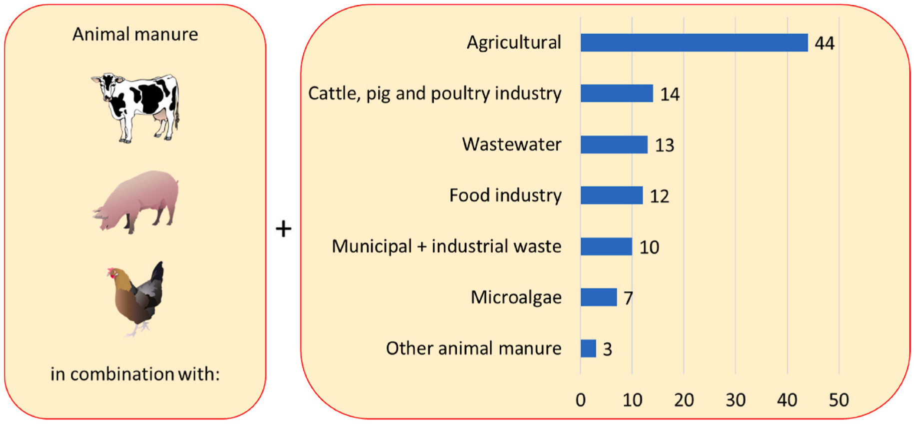


**Fig. 5.** Biomasses in combination with cattle, pig, and poultry manure (n. of the articles).

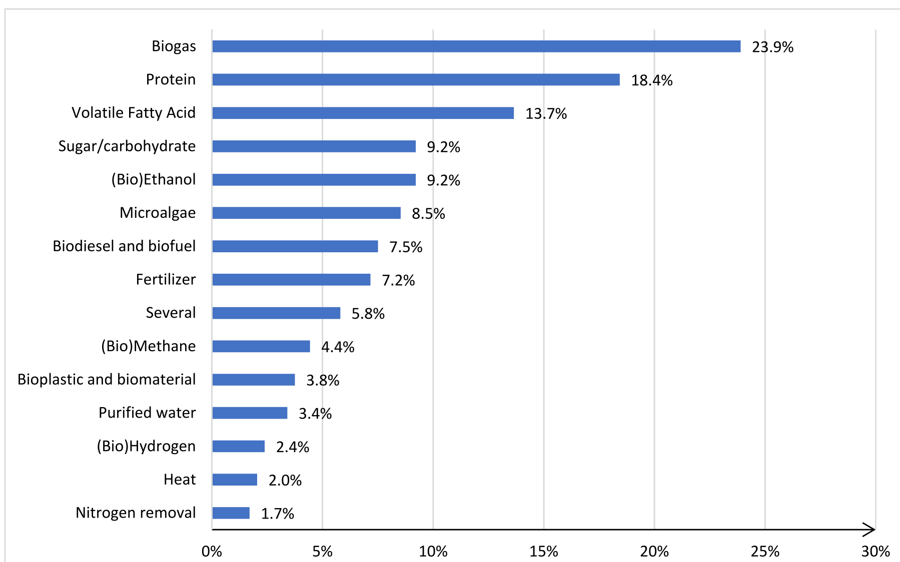


**Fig. 6.** Number of citations by bioproducts produced in the biorefinery process in the articles considered.

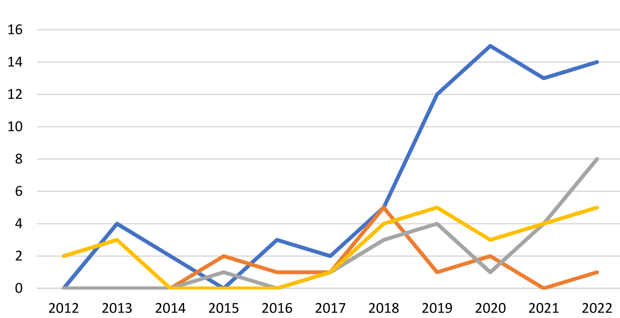


**Fig. 7.** Biogas, biomethane, biodiesel and biofuels and ethanol trends.

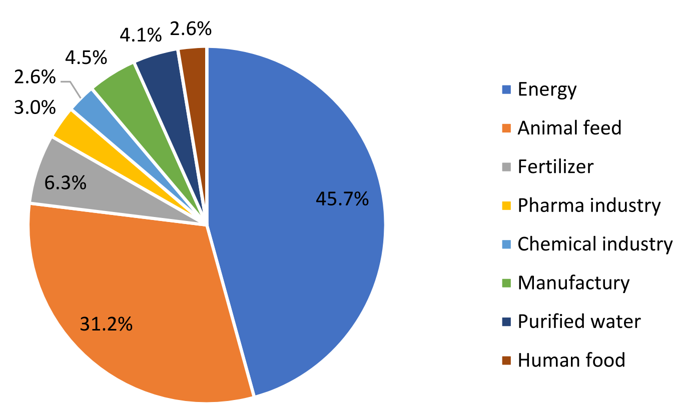


**Fig. 8.** Percentage of articles per economic/industrial sector of byproducts of the biorefinery.

obtained, the same consideration applies to the biomass of origin: in many articles, several bioproducts obtained are cited, so the total is higher than the number of articles considered.

The byproducts of the biorefinery were classified according to their intended use. The results confirm that biomass biorefineries are mainly directed towards energy production, with 123 articles (42.0%; Fig. 8). This condition has also increased in recent years (Fig. 7) and is likely to continue in the coming years, considering the emphasis on climate change and renewable energy. Another vital biomass utilisation sector is animal feed production, with 84 articles (28.7%). This sector is also growing, but with a slower trend; considering that much of the research in this area is techno-economic analysis and LCAs, this trend may be due to a relative maturity of the technology, which leads researchers and technicians to optimise existing solutions rather than to find new ones. In the agricultural and livestock sector, 17 papers, 5.8% of the total, concern fertiliser production. In most of these papers, fertiliser is only one of the bioproducts obtained; this proves the tendency of biorefinery research to work from a circular economy perspective, seeking to make the most of all available resources. Biomass produced in the livestock sector can also be used in various industrial sectors. In this analysis, the industrial sectors that used byproducts the most were the manufacturing sector (12 papers), the pharmaceutical industry (8 articles), and the chemical industry (7 papers). The production of food suitable for human consumption concerns a limited number of papers, 7 papers; these are review articles or processes that use agricultural or animal biomass to produce food suitable for both animals and humans.

### 3.3. Treatments applied, experimental scale and production environment

The treatments used in the biorefinery processes of the investigated research papers were analysed (Fig. 9). As expected, many techniques use several types of treatment, either sequentially or simultaneously, or use treatments that can be included in more than one category.

As noted earlier in the analysis of the review articles, anaerobic digestion is the most widely used treatment; 84 articles use it, almost a third of the total number of articles (28.7%). Anaerobic digestion is particularly well suited to treating liquid or semiliquid biomasses such as manure and livestock slurry. The widespread use of this treatment may be due to many factors: *i)* it can be applied to different types of biomass, not only manure or agricultural byproducts but also urban and industrial waste; *ii)* it allows biomass to be valorised from an energy point of view and as a byproduct produces digestate, which is also a valuable product because it can be used as a fertiliser; *iii)* it can be installed even in relatively small farms, agricultural or industrial, due to its relatively low costs and safe and regular earnings (biomethane).

Chemical treatments were applied in 80 studies, 27.3% of the total. Many different treatments belong to this category: alteration of pH, removal of metals, and composition or decomposition of organic and nonorganic compounds. They are mainly used for civil and industrial waste, as they often contain substances incompatible with their valorisation and must therefore be pre-treated.

Thermal treatments are also widespread (70 articles, 23.9%). These treatments can enhance the biomass directly: combustion and gasification; or they can serve to prepare the biomass for other combined treatments, for example, they serve to heat it or keep it at a specific temperature. Thermal energy valorisation processes are well suited for biomass with low water content, such as agricultural residues or certain types of industrial waste. Applying these treatments to manure is associated with pretreatments such as drying or desiccation, or they are applied to composite matrices consisting of manure and other agricultural byproducts.

Mechanical treatments include all modifications to the size and constitution of the biomass. They include grinding, crushing and filtering. They are mainly applied to solid agricultural biomass intended to produce animal feed. Filtration is often used to pre-treat wastewater from livestock farming and civil and industrial wastewater. This set includes 47 articles or 16% of the total.

Biological treatments included 47 articles, 16% of the total. This broad category includes fungi, microalgae, and bacteria cultivation. These treatments are particularly suitable for treating liquid biomass, especially wastewater and runoff; they are used as pre-treatments for removing metals and other substances. Biological processes are a very heterogeneous category; even more varied is how they are used, as in most biorefinery processes in which they are present, they are used in combination with other treatments.

For a better description of the biorefinery processes, it is possible to cross-reference the data on the type of process used with the scale of application of the study. In Fig. 10, it is possible to observe how production processes are developed in the laboratory, in pilot plants and at full scale. In all cases, laboratory processes are the most common, but with significant differences. Thermal, chemical and biological processes are almost exclusively carried out in the laboratory; this suggests that these technologies and techniques are still in the experimental phase and will be the subject of future research and development. In contrast, mechanical processes and those using anaerobic digestion are very often carried out in pilot or full-scale plants; these technologies are more mature and are being tested to improve their performance, cost-effectiveness or reduce their environmental impact.

In general, biorefinery processes require the installation of major facilities with a relatively advanced technological component. In the scientific literature, however, much research is carried out not in full-scale facilities but in the laboratory. Information on the scale of application of the research was collected. Most of the articles, 61.9% of the total, i.e., 125 papers, are carried out in the laboratory, i.e., in a very different environment from the real one, where the biorefinery will eventually be applied once the technology is mature. The topics covered in these papers are generally the most innovative, experimental ones.

A much smaller proportion of paper, 25 papers, 12.4% of the total, is carried out in pilot plants; these processes are generally situations with a more advanced degree of development. However, it is not always easy to distinguish between pilot plants and the laboratory; the choice was made primarily based on what the authors of the articles themselves stated in the methodology. Finally, 52 articles, 25.7% of the total, were carried out at full scale. Most of the technoeconomic studies and LCAs belong to this group. Another group of papers that were carried out on a full-scale basis are those that tested new diets for animals with food from the waste biomass biorefinery.

In Fig. 11, the methods used to conduct research in the published research are correlated with the biomass processing environment

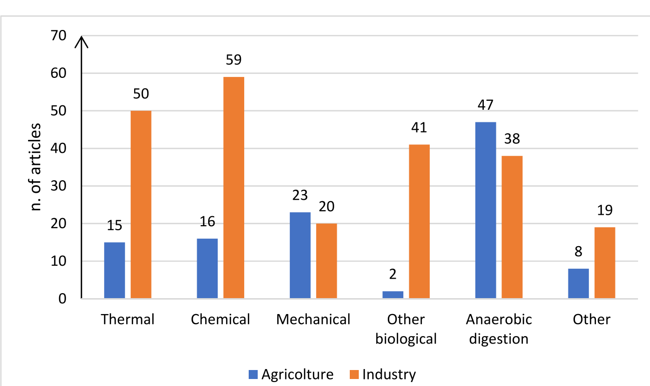


**Fig. 9.** Type of treatment used in the biorefining process combined with the context of the process.

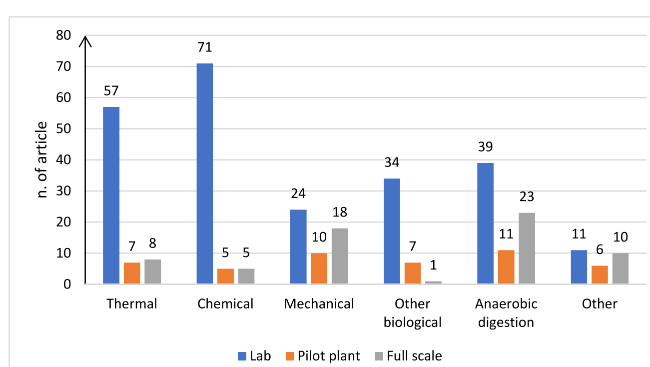


**Fig. 10.** Ways of setting up the research in the selected articles based on the biorefinery process type used.

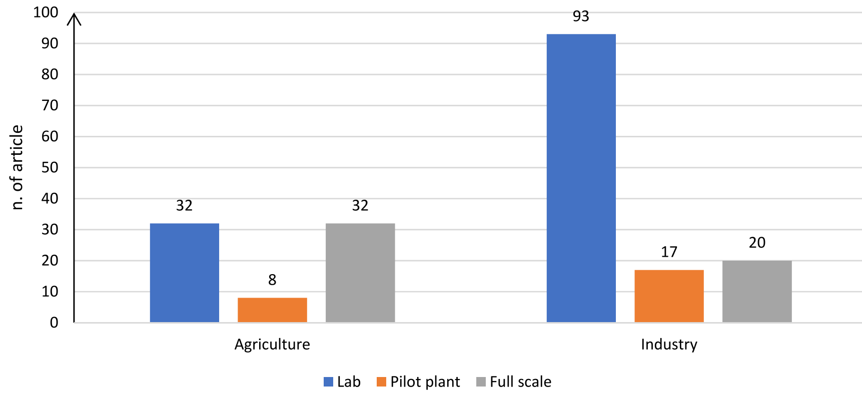


**Fig. 11.** Ways of setting up the research in the selected articles.

(farming or industrial). The results demonstrate that processes carried out in the agricultural context have good full-scale application, which are less applicable under laboratory and pilot plant conditions; this proves that the biorefinery is in a more mature condition and there is less innovation in this environment. The opposite is true for biorefinery processes conducted in an industrial context; in this condition, there are fewer full-scale applications and more at an experimental level, a sign that research is still at an experimental stage, with fewer real applications. For some articles, it was impossible to determine whether they belonged to one of the two categories because they were either review articles or LCAs, or the process was still in the experimental stage, and it was not possible to determine where it could be developed later.

These concepts will be addressed in Section 8, where future research perspectives will be presented.

### *3.4. Bioenergy production treatments*

Based on the articles examined, a description of the treatments used for bioenergy production can be provided.

Bioenergy production using manure allows for the valorisation of waste products and avoids competition with food crops; the benefits of this practice have been documented in the scientific literature: mitigating pollution due to their management (Catenacci et al., 2022), decreasing costs related to the nitrogen disposal process (Femeena et al., 2022), and obtaining digestate valuable as fertiliser (Feiz et al., 2021). One of the most significant benefits of bioenergy is the possibility of providing different types of energy, depending on the biomass available and the needs of the energy system: electricity, heat, and fuel or biofuel, through the process of upgrading methane in liquid or gaseous form. However, it is also necessary to carefully identify the conditions that enhance the environmental sustainability of bioenergy production (Li et al., 2022) and to develop innovative technologies to improve anaerobic digestion.

Anaerobic digestion is the process of generating biogas through a series of biomass degradation processes (Holl et al., 2022). Biogas can be used to produce electricity, heat and biofuels (Ferrari et al., 2022). The most widespread technology in Europe allows combined heat and power production in the same plant (Rekleitis et al., 2020). Anaerobic digesters are connected to a gas engine to produce heat and electricity with an installed capacity typically ranging from a few tens of kWe to several MWe (Sganzerla et al., 2022). The heat generated can also be used for the needs of the farm facility, as well as, of course, being delivered to external users. Biogas can be upgraded to produce biomethane, which can be injected into the natural gas transport grid or used as a vehicle fuel (Hamelin et al., 2021). Anaerobic digestion is an established technology and has been extensively studied (Rekleitis et al., 2020). Today, work on biogas is focusing on diversifying biomass, experimenting with new matrices and new combinations of feedstocks (Karki et al., 2021), increasing yields, improving process efficiency and refining resource management (Kassem et al., 2020). However, anaerobic digestion is not the only valid process for biomass valorisation; thermochemical valorisation processes cannot be overlooked among the most widespread and effective systems.

Combustion is a thermochemical process for the utilisation of organic waste. This process is particularly suitable for biomass with a low moisture content (less than 20%) (Azwar et al., 2022). The hot gases obtained from the combustion process mainly comprise $CO_2$ and water vapour, and the steam generated can be efficiently used to power a steam turbine for energy generation (Bora et al., 2020). The end product of the combustion process is heat and other gases. This technology is particularly convenient in areas with a cold climate, where the high demand for heat makes the plants economically viable. Additionally, this technology is advantageous in developed countries with high population density, where the possibility of reducing the volumes and costs of managing the organic fraction of solid waste is significant (Odales-Bernal et al., 2021).

Using combustion for livestock manure management is not a typical process, as this raw material has a high water content (Cavinato et al., 2017). However, drying, torrefaction and pelletisation processes can be adopted to utilise this matrix efficiently with this process (Khoshnevisan et al., 2021a), or manure can be used in combination with other biomasses (Karki et al., 2021). The combustion process produces many gases and ash: carbon monoxide, nitrogen oxides and acid gases such as sulfur dioxide. Because of these emissions, phosphorus and potassium recovery technologies from livestock manure intended for combustion have recently become widespread (Awasthi et al., 2019).

Technologies for recovering nutrients from waste and byproducts, such as livestock manure, are becoming increasingly common. Manure, especially the liquid fraction, contains significant amounts of nitrogen and phosphorous (Cavinato et al., 2017). In areas with intensive livestock activity, this can cause severe problems of oversupply of these nutrients as fertilisers and lead to soil acidification and eutrophication (Møller et al., 2022). The recovered nutrients can be further exploited by producing biomaterials and bioproducts. Among the most popular recovery processes are ammonia stripping, chemical precipitation, ion exchange, membrane separation, and thermal treatments.

Ammonia stripping takes place in stripping towers; in these facilities, the nitrogen available in the liquid substrate passes into the gas phase in the form of $NH_3$. Ammonia stripping is a relatively simple process, but attention must be paid to pH control and aeration. Another method of nutrient recovery is the precipitation of struvite, which allows the recovery of nitrogen and phosphorous. The most significant advantage of struvite formation is the low energy demand, while the low percentage of recovered nitrogen is the main drawback (Vaneeckhaute et al., 2019).

Membrane technologies, such as reverse osmosis, nanofiltration, membrane distillation, and electrodialysis, have excellent performance in recovering resources from liquid biomass. These technologies can be divided into pressure and non-pressure technologies. Pressure-based membrane filtration requires an energy of 4–6 kWh/m$^3$ and an operating cost of 4–13 €/m$^3$ in operational plants (according to a study conducted on several situations in different countries of the world) (Khoshnevisan et al., 2021b). Filtration and reverse osmosis are classified among the pressure membrane technologies. Generally, these technologies are unsuitable for manure treatment, as manure contains a high value of organic matter and total solids (TS). However, they are well suited to treating digestate or the liquid fraction of animal slurry (Khoshnevisan et al., 2021b). The choice between different pre-treatments for nutrient removal and valorisation systems (bioenergy, bioproducts) depends on the biomass characteristics and environmental requirements.

## 4. Review article analysis

The first analysis focused on review articles. Biorefineries involve numerous topics; for this reason, research has followed various directions that are also very different. Consequently, many authors have periodically reviewed scientific advances in this multidisciplinary field with numerous review articles. These articles were analysed, and key themes and features were derived.

To include this work within the framework of previous reviews, the most significant review articles in animal livestock were summarised first (Table 2). The application of biorefinery processes to livestock manure has mainly concerned energy production. Among the first authors to summarise the scientific conclusions, Awasthi et al. (2019) and Khoshnevisan et al. (2021b) analysed both biogas and digestate production for agronomic purposes. They considered manure produced by different types of animals, cattle, pigs, and poultry, and concluded that livestock manure management could replace 60–75% synthetic fertiliser with some extra gain in bioenergy and nutrients. Other authors have directed the review towards a particular species of animal, e.g., cattle (Mandavgane and Kulkarni, 2020), pigs (Walowsky, 2021), or poultry (Alba Reyes et al., 2021). However, the use of manure is not limited to energy production: Zhu and Hiltunen (2016); Zhu et al. (2021), summarised the state of the art regarding the cultivation of microalgae with farm manure. The results demonstrated that pretreatment of dry matter before conversion is required to obtain a high sugar yield for microbial fermentation because, in general, dry matter substrates have lower carbohydrate content relative to other substrates. Different pre-treatments showed their advantages and disadvantages regarding the efficiency, formation of inhibitors, energy consumption, and process costs.

One of the essential aspects of the research was the integration of livestock manure with other byproducts of agricultural origin. This combination fully meets the need to develop a circular economy: within the same production centre, the agro-livestock farm, various productions can be combined to exploit the characteristics of the respective biomasses produced. In Li et al., 2012), Rekleitis et al. (2020); Mendes et al. (2022), the results of integrating farm waste with agricultural byproducts are analysed. In Catenacci et al., 2022) and Nzeteu et al. (2022), the analysis is directed at the results of integrating manure with food waste. With a combination of these biomasses, the integration of waste management in agricultural and civil/urban areas is realised. Moreover, Catenacci et al., 2022 demonstrated the advantages of combining the digestate as a fertiliser and its energetic valorisation to

**Table 2**
Analysis of previous review articles.

| Topic | Year | Biomass used | Bioproduct(s) | Treatment(s) | Reference |
|---|---|---|---|---|---|
| Valorisation potential of various sustainably sourced feedstocks, particularly food wastes and agricultural and animal residues | 2022 | Food waste, grass and manure | Biogas, bioproducts, VFA | n.s. | Nzeteu et al. (2022) |
| Anaerobic digestion integration with pyrolysis/HTC, digestate as feedstocks for char production | 2022 | Food waste, agricultural byproducts and manure | Biogas | n.s. | Catenacci et al. (2022) |
| Techno-economic assessment and life cycle assessment of livestock manure management operation in the context of their economic and environmental sustainability | 2022 | Cattle, pig, poultry farm manure | Biogas, nutrient recover | AD | Awasthi et al. (2022) |
| Bibliographical survey of biomass generated in Brazilian agroindustry as a cosubstrate for energy production | 2022 | Agricultural byproducts, cattle, pig and poultry manure | Biogas | AD | Mendes et al. (2022) |
| Enrichment strategy of gut microbial community and its molecular characterisation techniques to understand the holistic microbial community dynamics. | 2021 | Insects and ruminant manure and waste | Biofuel | n.s. | Rajeswari et al. (2021) |
| Review of different types of bioenergy production from dairy manure and provided a general overview for bioenergy production | 2021 | Cattle manure | Biogas, bioethanol, biohydrogen, microbial fuel cell, lactic acid | AD | Zhu et al. (2021) |
| Sustainable pathways to maximise the PL valorisation process, and showing the advantages of reforming poultry farms into biorefineries in Cuba | 2021 | Poultry manure | Several energy products | Thermochemical processes and AD | Odales-Bernal et al. (2021) |
| Current leachate processes that could be applied as a previous step during the AD of CM, in addition to deep on the state of the art of HRAR using CM leachate as a liquid substrate for AD | 2021 | Poultry manure | Biogas | AD | Alba Reyes et al. (2021) |
| Systems and technological variants of biogas production | 2021 | Pig manure | Biogas | AD | Walowsky (2021) |
| Most employed manure management technologies, challenges, sustainability, environmental regulations and incentives, improvement strategies perspectives | 2021 | Livestock manure | Several products: energy, fertiliser | n.s. | Khoshnevisan et al. (2021b) |
| Biorefinery biomass technology, energy production technology, production of biofuels, and new materials from waste biomass at the behest of the circular economy and bioeconomy | 2020 | Agricultural and livestock waste | Bioenergy | n.s. | Rekleitis et al. (2020) |
| Physicochemical composition and valorisation of cow urine and dung. | 2020 | Cattle manure | Biogas, digestate | AD | Mandavgane and Kulkarni (2020) |
| Review of organic manure biorefinery models towards sustainable circular bioeconomy | 2019 | Livestock manure | Biogas, digestate | AD | Awasthi et al. (2019) |
| Microalgal cultivation with livestock waste compost for continuous production of multiple bioproducts | 2016 | Livestock manure | n.s. | Microalgae cultivation | Zhu and Hiltunen (2016) |

produce char.

An interesting aspect is the management of animal manure in combination with insects. A fascinating examination of this area is provided by Rajeswari et al. (2021), who analysed gut microbial community enrichment strategies and molecular characterisation techniques to understand microbial community dynamics of several insects and ruminants for second generation production of biofuels and chemicals. According to the authors, to strengthen the perspective of the second-generation biofuels industry, implementing a centralised market is required to provide homogenous supply routes and an integrated bioprocess strategy for the cost competitiveness of these biofuels.

Anaerobic digestion is the most widely used process for the treatment of biomass. Numerous authors have conducted studies applying this technique, and multiple review articles have summarised them; interest in this area is still high. For example, Pelaez-Samaniego et al. (2017) and Sevillano et al. (2021) summarised the results of anaerobic digestion of manure, particularly cattle manure, in combination with agricultural products, showing the advantages of using these biomasses in combination on heavy metal accumulation, increased soil salinity, phytotoxicity, and ecotoxicity. The study by Karki et al. (2021) is on this topic; they examined the state of the art of anaerobic digestion, in particular showing the limitations of mono-digestion, compared with the advantages of systems that use multiple substrates: synergistic interactions via balance of nutrients, supplementation of trace elements, dilution of toxic and inhibitory compounds, and promotion of microbial diversity to maintain diverse microbial communities during long-term codigestion.

Over the years, research interest has grown in one particular sector, the dairy industry. The increase in research in this area has led to a rise in the frequency of publication of review articles: one article in 2018 (Chandra et al., 2018), two articles in 2020 (Asunis et al., 2020; Sebastián-Nicolás et al., 2020) and 2021 (Carvalho et al., 2021; Zandona et al., 2021) and three articles in 2022 (Gottardo et al., 2022; Kumar Awasthi et al., 2022; Sar et al., 2022). This type of industry produces a significant amount of biomass in liquid form, with enough organic matter to generate considerable energy.

The growing interest in the circular economy has increased the focus on the economic and environmental consequences and costs of products and processes. In response to the need to optimise investments and reduce the consumption of resources and the production of pollutants, many authors have carried out techno-economic analyses of processes and LCAs of products. This scientific production has also covered less available but essential products. For example, Odales-Bernal et al. (2021) summarised research on poultry litter exploitation to propose optimised systems for exploiting this biomass and promoting its use; they concluded that the treatment of poultry litter in biorefineries in Cuba would have a positive impact on the economy through income generation and savings resulting from reductions in imports (i.e., fossil fuels and agrochemicals), employment creation, improved living conditions and development in rural communities. Awasthi et al. (2022) summarised the scientific findings regarding the environmental impacts of livestock manure management; through the analysis of various life cycle assessments and technoeconomic assessments, they composed a state-of-the-art picture and indicated exciting perspectives for research and regulations and policies in the field.

## 5. LCA papers and techno-economic analysis

Research in biorefineries has not only focused on chemistry or the physics of processes (Li et al., 2022). Often, industries intend to use established technologies but must verify the technical feasibility and economic viability of applying specific methods (Rhee et al., 2021). For this reason, research has focused on the technical-economic feasibility instead of the experimental-scientific feasibility.

Most of the technical analyses relate to processes involving cattle breeding. However, in contrast to other studies, in addition to the interest in products and processes that utilise manure, a considerable interest of researchers can be observed in the production of biomass destined for cattle farming, particularly for food production. The research of Demichelis et al. (2019); Kassem et al. (2020) belongs to the first group of studies. These authors set the analysis on a large scale, calculating the environmental impact of cattle manure uses for large study areas. Demichelis et al. (2019) developed a method for the environmental and technical quantification of biowaste management in Italy. Through a geolocation system of waste and knowing its characteristics, it is possible to determine the best process for its valorisation.

Interestingly, the same authors (Demichelis et al., 2019) later extended the analysis to a European level, testing it on a larger scale. Kassem et al. (2020) implemented a system combining various valorisation processes to quantify the expense and economic return of utilising the manure produced by 397,000 cattle in New York State. On the other hand, Joglekar et al. (2020) focused their studies on one particular process and quantified the sustainability of a biorefinery using cattle manure, applying a sustainability index based on a multicriteria analysis. Another innovative approach was studied by Rhee et al. (2021), who combined manure with microalgae for energy production. The utilisation of microalgae is also confirmed as a promising area from a technoeconomic point of view; this supports the idea that extensive applied research will have to be devoted to this area in the future. Finally, the use of agricultural biomass for cattle feed production was discussed in two papers, both from Brazil and both using sugar cane as a crop for nutrient production. Junqueira et al. (2018) used a digital architecture to simulate an ethanol production process for cattle feed. Additionally, de Souza et al., 2019 used digital simulation models; in this case, cattle pasture was integrated with sugarcane cultivation, and the possible savings in $CO_2$ emissions using this system were simulated.

Of course, cattle are not the only source of manure investigated by researchers. Pig manure management can become a significant issue, especially since this type of livestock farming tends to be concentrated in specific geographical areas. These analyses were carried out by Vaneeckhaute et al. (2019) in Canada and Lee and Tsai (2020) in Taiwan; these authors used data libraries to quantify the volumes of biomass generated by pig farming and the environmental benefits of proper management. The agronomic aspect is addressed in the work of Tampio et al. (2019), who studied the effects on the phosphorous and nitrogen cycle of fodder cultivation in combination with pig farming: animal feeding, soil fertilisation and anaerobic digestion are the steps/processes in which the two biomasses are integrated. The high energy value of poultry manure makes this biomass particularly suitable for thermal processes. Tao and You (2020); Bora et al. (2020), studied this topic; the first one from a geographical point of view, identifying the most advantageous supply chains in New York State; the second one by comparing alternative processes for energy valorisation in nine plants and calculating the respective costs and gains.

As previously described, anaerobic digestion is the most widely used process for biomass valorisation. In this area, technoeconomic analyses follow three approaches: *i)* the planning of interventions, with the forecasting of costs and economic and environmental gains from the construction and use of the plants (Bramstoft et al., 2020); *ii)* the verification of actions taken, especially of legislative and regulatory initiatives in particular geographical/administrative areas (Curry et al., 2018); and *iii)* the review of the literature, with a periodic update of the state of the art of the technology (Sevillano et al., 2021).

Studies that did not use biomass from livestock farming but used various biomasses to produce bioproducts for animals, mainly feed, were analysed. It was illustrated that the use of agricultural byproducts for the production of animal feed is widespread; the analysis showed that in this area, many technoeconomic studies were directed towards the evaluation of processes for ethanol production (Turner and Saville, 2022; Vaskan et al., 2018; Weinwurm et al., 2013). In other research, ethanol production combines agricultural byproducts with livestock manure. Li et al. (2022); Capaz et al. (2021) evaluated the viability of processes that use a mix of animal and plant biomasses to produce ethanol for use as biofuel, the first for maritime transport and the second for air transport.

It is interesting to note the work of Guilayn et al. (2020), who studied the benefits of using digestate as a fertiliser and a thermal energy source. The study demonstrated the need to analyse the costs and gains of each step of the biorefinery to set up an efficient circular economy of biomass.

The large number of processes and technological solutions that research and technology have made available allows a certain freedom of choice in defining the tools available to achieve production goals. For this reason, in addition to scientific experimentation and technical-economic characterisation, to choose one process or product over another, it is necessary to compare alternatives based on their overall emissions over their entire life cycle (Table 3). Life cycle assessment has precisely this objective, and numerous authors have applied this concept in the biorefinery of products from and for livestock farming.

The importance and spread of the dairy industry and the high volumes of wastewater produced, with the associated costs, have led many authors to evaluate, from an environmental point of view, several alternatives for their treatment. Kopperi and Mohan (2022) assessed the feasibility of a biorefinery process that uses wastewater from the dairy industry to produce microalgae; the microalgae are then used to produce energy. In this way, wastewater, a waste product, is valorised and undergoes an initial purification treatment. An interesting example of a complete life cycle is that offered by Ivanov et al. (2022), who analysed the combined life cycle of the dairy industry, the wastewater supply chain from production industries to treatment sites, and biodiesel production from the same.

Ethanol production remains of interest and topicality. Indeed, numerous researchers have analysed and compared alternative processes to determine the best conditions for production. In Brazil, land consumption for sugarcane ethanol production, cattle breeding and forest conservation is particularly important given the scale of the uses mentioned above; the topic was investigated by de Souza et al. (2019), who studied sugarcane ethanol production in combination with cattle breeding to avoid the consumption of forest area. In Europe ethanol production is linked to sugar beet; in Demichelis et al. (2020), this possibility was compared with the use of cattle manure, agricultural byproducts and municipal solid waste. Interestingly, while sugar beet is the most economically viable biomass, animal manure is environmentally preferable. The results showed how important it is to define the objectives of the processes, as calculations alone are insufficient to determine the absolute best alternative.

Cow manure is the most widely used biomass in animal husbandry, which is also demonstrated in LCA analyses. Usually, studies consider this biomass in combination with others to improve its performance. Among the others, the use of algae is one of the most promising choices: the production of biodiesel with different mixes of microalgae and cattle manure was studied by Maranduba et al. (2015); the results showed the advantages of this choice, as in scenarios where the two biomasses are used in combination, a reduction in GHG emissions of 53.6% and 63.8% is achieved, depending on the process used. Manure can also be used in combination with agricultural biomass. For example, in Vega et al. (2019), manure is used together with grape pomace to produce biogas and biomaterials; the comparison showed that combined bioenergy-biomaterial production is the most cost-effective because it makes full use of the available resources.

Remaining in cattle livestock, several authors have tested the impact of different animal diets, combining various types of biomasses from agricultural and other activities. Patterson et al. (2021) compared the use of hay for cattle feeding with its use to produce certain types of materials; in this way, they could estimate the environmental benefit of reducing meat consumption and the consequent use of hay for other processes. Even more specific is the topic addressed by Taelman et al. (2015), who compared the emissions of soya-based animal feed production and the same production based on algae. The results indicated that seaweed has a significantly higher carbon footprint; however, in their discussions, the authors attributed this result to the economies of scale present for soya but not for seaweed, the cultivation of which is still not widespread on an industrial scale.

In addition to cattle manure, other livestock biomasses are used. In Parajuli et al., 2018), cattle manure and pig manure were combined in different mixes for bioenergy production; the authors found that codigestion is the solution with the lowest emissions. The research of Moretti et al. (2018), who combined organic solid waste with cattle manure, should also be mentioned regarding this topic; the results again confirmed that codigestion is the best solution to reduce GHG emissions. In recent years, the exploitation of insects for energy and biomaterials has been gaining ground. Rosa et al. (2020) quantified the emissions from producing biomaterials derived from proteins extracted from black soldier fly larvae; the larvae grew on poultry manure. As in the case of cattle, the authors were interested in assessing the environmental impact of alternative diets, which allow animals to be fed using waste biomass while limiting land use for dedicated crops for other livestock farms, particularly pigs. LCAs of two grass- and grain-based diets were proposed by Cong and Termansen (2016) to reduce the environmental impact of pig farming, which is a significant problem in Denmark. Their results showed that the protein-based diet from the grass biorefinery reduces the feed cost, produces additional gains for the biorefinery and reduces nitrogen leaching. More recently, Møller et al. (2022) proposed a similar study on the sustainability of pig production based on a diet containing yeast as a protein source. This yeast-based diet is compared to a classic soy-based diet. The environmental impacts of the two systems were compared using LCA; the results proved that replacing soya with a yeast-based diet reduces environmental impacts in terms of biodiversity loss and climate change. This research allowed a comparison of the different systems also considering land consumption and showed that the biorefinery provides significant resource savings, reducing the impact on natural and forest areas.

## 6. Temporal trends and future challenges of research

Research interest in the biorefinery of biomass from livestock has grown in recent years. Fig. 12 shows the biorefinery growth trends for three of the main bioproducts obtained.

The growth of interest is mainly due to biorefineries for bioenergy production. In the category "Energy", anaerobic digestion and bioethanol production are the most widely used processes. However, a critical examination of the articles shows that this process is often conducted using traditional methods, as this is an established and widespread technology. In most cases, research focuses on process optimisation or evaluating matrices other than traditional matrices, which often use uncommon products. Although the number of articles on anaerobic digestion has increased very abruptly over the past four years compared to the previous 7, this research contribution now appears to have reached a stage of stability. These considerations lead one to think that research in biorefineries will have to turn towards other forms of bioenergy, such as biofuels or upgrading systems, areas that exist but where there is still considerable scope for development.

Nevertheless, in environmental sustainability, many authors have directed their efforts towards research dedicated to reducing the environmental impact and land consumption of livestock activities; in particular, many authors have demonstrated the importance of reducing the land consumption devoted to crops for animal feed production. Therefore, research into the production of ethanol, protein and other nutrients from agricultural byproducts and waste and from insect farming has gradually increased over the years. In particular, scientific contributions concerning insect breeding in biorefineries were very scarce until 2018 (only two registered articles) and were concentrated in the last four years, from 2019 to 2022 (18 articles).

The analysis of the articles made it possible to describe the areas of development of bioenergy, the objectives, and drivers for the development of these processes (Fig. 13A). Many authors recommend the

**Table 3**
Life cycle assessment process for manure management sustainability.

| Topic | Biomass used | Scale | Sector | Bioproduct(s) | Object of LCA | Main results | Reference |
|---|---|---|---|---|---|---|---|
| Optimal design of a sustainable combined supply chain to produce biodiesel | Dairy manure | Full scale | Agricultural | Biodiesel | Biodiesel from dairy waste | Total cost of the optimal supply chain: 10,593,364 $ | Ivanov et al. (2022) |
| Integration of dairy wastewater treatment, hydrothermal liquefaction of defatted algal biomass, and acidogenic process in a semisynthetic framework | Dairy wastewater | Pilot plant and full scale | Industry | Microalgae for pharma industry | Microalgae from dairy waste | Total bio-H2 production of 231 ml/g of TOC with a 63% treatment efficiency. | Kopperi and Mohan (2022) |
| Analysis of the sustainability of pig production based on a diet containing yeast as a protein source | Wood | Lab and pilot plant | n.s | Yeast to produce sugar | Yeast to produce sugar | Feed production causes: 64% of climate change, 70% of climate change and 100% of the land occupation | Møller et al. (2022) |
| Evaluation the utilising grass to produce high value products, specifically PHA biopolymers, in a biorefinery approach | Grass | Full scale | n.s | Protein | Feed for cattle from grass | A total of 30,000 t of fresh grass would yield approximately 403.65 t of dried biopoly- mer granules | Patterson et al. (2021) |
| Technical, economic and environmental assessment of bioethanol production from waste biomass | Sugarcane, potatoes, rice straw, cattle manure and OFMSW | n.s. | Agricultural and industry | Bioethanol | Ethanol from different agricultural and livestock manure | 0.19 kg of bioethanol per kg of cattle manure | Demichelis et al. (2020) |
| Comparison of the environmental sustainability assessments of different extraction/ fractionation procedures | Poultry farm | n.s. | Industrial | Protein | Bioproducts from larvae of BSF from poultry manure | The enzymatic approach resulted for the 31.87% more environmentally impacting with respect to the chemical method. | Rosa et al. (2020) |
| Examining environmental impacts arising from technology-to-region compatibility, the framework is applied to two biorefinery alternatives, treating a mixture of cow manure and grape marc. | Cow manure and grape marc | Full scale | n.s. | Biogas and PHA | Biogas or biomaterials from cattle manure | 1.59 and 1.40 person-equivalent of avoided GWP per ton of treated feedstock per day in France and Oregon, respectively | Vega et al. (2019) |
| Techno-economic and environmental feasibility of sugarcane ethanol and cattle integration | Sugarcane | n.s. | n.s. | Bioethanol | Ethanol from sugarcane for cattle feeding | 0.9 kg $CO_2$eq per kg of ethanol; 0.5 kg $CO_2$eq per kg of sugar and 0.08 kg $CO_2$eq per kWh of electricity produced | de Souza et al. (2019) |
| Effect of time on bioenergy production from dairy manure and associated variation in energy demand and GHG emission | Cattle manure | Full scale | Agricultural | Biogas | Bioenergy from cattle manure from different resident time | 28–35 kg $CO_2$/GJ of bioenergy produced | Chowdhury et al. (2018) |
| Evaluate the environmental impacts of a combined production of suckler cow calves and Pigs, calculated in terms of their live weight | Cattle and pig manure | Full scale | Agricultural | Biomethane | Three bioenergy production systems from cattle and pig manure | 1 kg of cattle manure and 1 kg of pig manure produce 19.6 kg $CO_2$ eq for carbon footprint | Parajuli et al. (2018) |
| LCA of two scenarios for the biological treatment of local organic municipal solid waste and pig manure in the Netherlands | Organic municipal solid waste and pig manure | Full scale | Industrial | Biogas | AD of two diets with OMSW and pig manure | 0.17 Mt $CO_2$ eq./yr for Scenario 1 and 0.16 Mt $CO_2$ eq./yr for Scenario 2 | Moretti et al. (2018) |
| LCA of three cattle manure biorefineries: first and second scenarios, the biogas is used for electricity and transportation; third scenario, the biogas is recycled back to the systems | Cattle manure | Full scale | n.s. | Biogas | AD of two diets with macroalgae and cattle manure | The life cycle of biogas production from cattle manure is 2017 mPt | Giwa (2017) |
| Comparison of the economic and environmental effects of producing the pig feed using two feeding systems | Grass | Full scale | Agricultural | Protein | Two pig feed with grass and cereals | To produce 1 ton of pork, with the cereal-based feeding system roughly 0.61 ton barley and 0.2 ton soya are needed | Cong and Termansen (2016) |
| Analysis of the biodiesel production system via dry-route, based on Chlorella vulgaris cultivated in raceways, by comparing the GHG-footprints of diverse microalgae-biodiesel scenarios | Cattle manure | n.s. | n.s. | Biodiesel | Five mix of microalgae and cattle manure for biodiesel production | The C1 and C2 scenarios presented GHG emissions of 5.10 and 4.88 t CO2-eq/t biodiesel, respectively | Maranduba et al. (2015) |
| Sustainability in terms of the natural resource demands of protein-rich algal meal (versus soybean) for livestock feed applications | Microalgae, soybean | Pilot plant | n.s. | Protein | Microalgae and soybean for animal feed | the most exergetically inefficient pro-cesses are anaerobic digestion (66.47%), condensation (56.53% and 63.81%), inoculum production (54.98%) and drying (44.01%) | Taelman et al. (2015) |

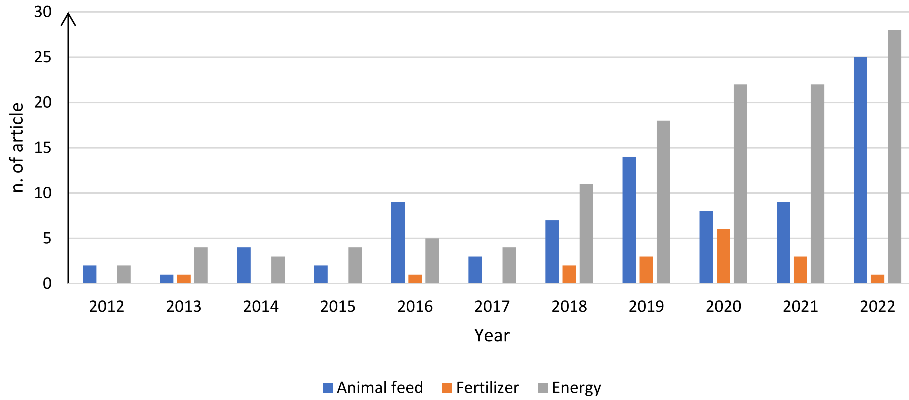


**Fig. 12.** Temporal trends of scientific articles.

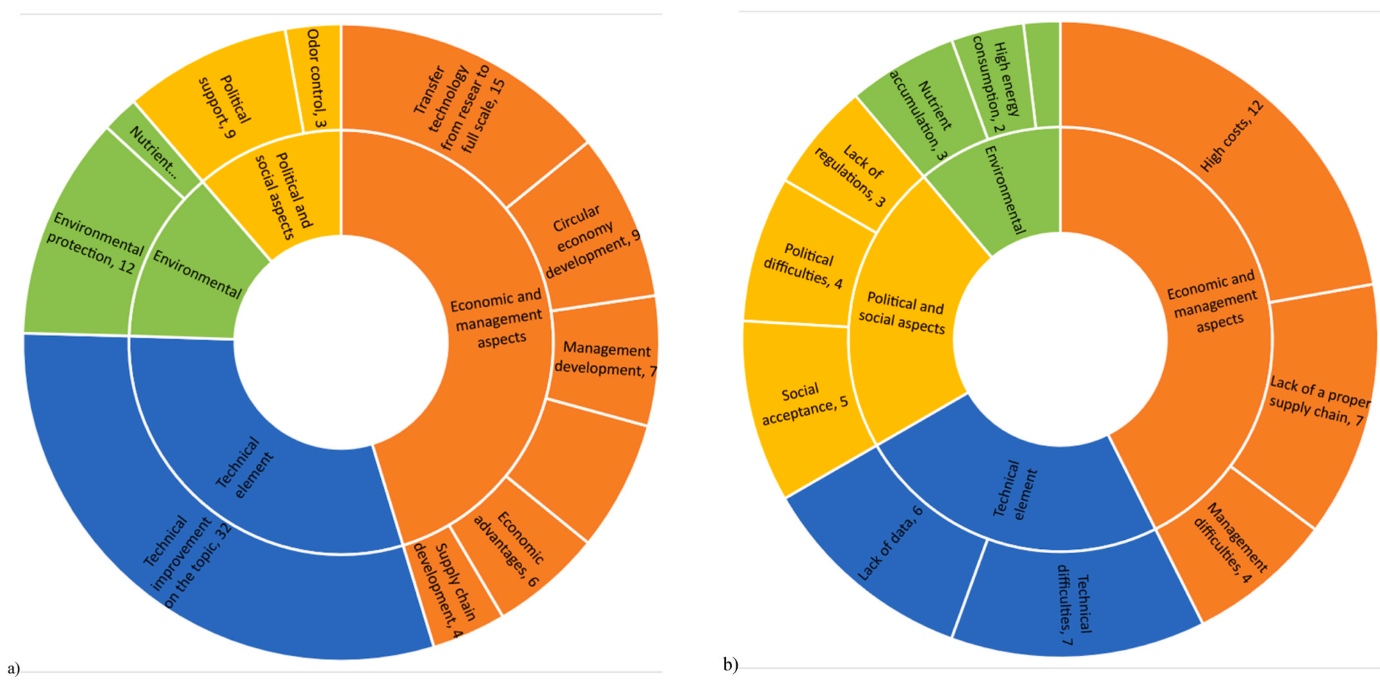


**Fig. 13.** (a) Possible areas of study, objectives, stimulating elements and (b) possible obstacles and elements of resistance to the spread of biorefineries.

development of methods and the improvement of technology; these objectives are particularly important regarding insect breeding, a relatively new field. Most scientific contributions recommend focusing on economic and management aspects. The transition from laboratory processes to full-scale plants requires testing technologies on progressively larger plants. For the complete application of biorefinery processes, it is necessary to undertake cost-cutting paths. Furthermore, exploiting the economic benefits derived from integrated resource utilisation approaches is necessary, a vision closely linked to the circular economy. Particular attention must be paid to the supply chain; many authors see the irregularity and seasonality of biomass as a possible point of weakness (and thus improvement) for the sector. Other authors identify environmental benefits as an essential driver for developing biorefineries. It is worth emphasising that, for many researchers, political support and the definition of rules and incentives are positive and, in some cases, necessary to spread these processes.

Alongside the positive and developmental elements, the analysis of the articles identified obstacles and aspects of resistance to the spread of biorefineries (Fig. 13b). Biorefinery processes are still seen as very expensive, which hinders their spread on an industrial scale. This difficulty leads to a lack of reliable data on the application of these technologies in the real environment; much research is carried out in the laboratory or in pilot plants, which is why it is not easy to estimate the convenience and impact of the same processes in industrial plants. The same applies to management practices, which are still insufficient to guarantee full process reliability. Some authors see the lack of suitable politics as a possible brake on the spread of biorefining. The population still views these technologies with distrust, partly due to the lack of reliable regulations.

It should be noted that for many authors, some biorefinery processes can also undermine environmental protection. Indeed, local nutrient accumulation problems arise as a result of biomass exploitation. Furthermore, many processes are still significant energy and natural resource consumers.

## 7. Conclusion

This paper proposes an analysis of scientific articles on biorefinery processes applied in the livestock sector. Both processes that exploit biomass from livestock farming and processes that exploit biomass to produce livestock products were considered. A total of 293 articles published between 2012 and 2022 were analysed. Most articles use manure as biomass, 123 articles, while the most considered product is bioenergy production, 123 articles. Finally, review articles, LCAs and technoeconomic articles were analysed to provide a comprehensive global view of the topic. Based on the achieved results, three key elements can be summarised:

i) Interest in the biorefinery of animal byproducts has steadily increased in recent years. The results confirmed the conclusions of previous studies; in fact, the most commonly used treatment was anaerobic digestion, with 84 articles. Research interest in this topic is steadily increasing; however, it is still linked to traditional processes and products, anaerobic digestion, and biogas.
ii) Currently, promising new areas of research are emerging. Concerning the biomasses used, new combinations between livestock manure and other biomasses, whether agricultural or civil/industrial, are being experimented with; in addition, insects, which can be an essential source of proteins and carbohydrates in all areas of biorefineries, are gaining attention. In terms of uses, biofuels are an area of significant research interest, an interest that is consistent with the policies of many institutions.
iii) Concerning the future direction of research, two scenarios can be imagined. If research is still autonomous in its choice of objectives, the use of livestock biomasses will probably continue to be applied to energy production and animal feed production; the cultivation of microalgae in liquid biomasses and the breeding of insects will likely gain importance. On the other hand, in the presence of a policy direction and, possibly, a system of incentives, the work of researchers and technicians may be directed more towards fields that are currently less explored, such as the production of bioproducts for the building industry or the manufacturing industry. In both cases, innovations will certainly involve insect breeding, an up-and-coming sector in various applications: food production, animal feed, purification of wastewater, etc.

This analysis was limited to studying biorefineries in animal husbandry and did not devote as much attention to agriculture in general. The investigation could also be deepened by examining the different species of insects and other microorganisms involved in biorefining.

In conclusion, the results obtained confirmed and emphasised the role of biorefineries in livestock production systems in reducing the environmental impact of the agricultural system and in contributing to reducing the use of resources in other sectors.

## CRediT authorship contribution statement

**Giovanni Ferrari:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft. **Giorgio Provolo:** Visualization, Writing – review & editing. **Stefania Pindozzi:** Visualization, Writing – review & editing. **Francesco Marinello:** Visualization, Writing – review & editing. **Andrea Pezzuolo:** Conceptualization, Investigation, Methodology, Resources, Supervision, Validation, Writing – original draft.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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