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Advances in the insect industry within a circular bioeconomy context: a research agenda

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Abstract
The agri-food industry is increasingly recognizing the environmental impact of the over-exploitation of natural resources and waste production, which has prompted a search for sustainable alternatives based on circular bioeconomy principles. Insects can efficiently transform food substrates into reusable biomass, thus making them valuable contributors to a circular bioeconomy system. However, the relationship between the circular bioeconomy and the insect industry has so far appeared relatively unexplored in the existing research. To address this gap, a meta-synthesis has been conducted through a systematic literature review. By identifying the state of the art and assessing the role of insects in the transition of closed-loop systems, the aim of this research has been to shed light on the opportunities and challenges of integrating insects in circular bioeconomy strategies. The research revealed three main topics: (1) waste management by insects, i.e., the use of insects as a tool for waste management and with which to create high-value substrates; (2) insect-based feeds, namely the use of insects as alternative food sources in farming systems; (3) insect-based food acceptance by consumers. The results underscore the significant potential of this market within the circular bioeconomy context, highlighting the obstacles that need to be addressed and future strategies that could be adopted.

Keywords Circular economy, Waste management, Bioconversion, Insects–based feeds, Insect–based food, Social acceptance

Introduction

Agri-food systems are currently facing a wide range of complex challenges due to the decrease in the availability of agricultural land, climate change [1], the threat of dwindling water resources [2], and the pollution of aquatic and terrestrial ecosystems [3]. The area of land involved in agricultural activities is gradually shrinking and simulations have predicted that the yield per hectare of cereals and other important crops may soon decrease, due to specific soil and climate conditions [4].

Considering that, according to the United Nations (UN) report [5], the population is expected to reach 9.7 billion by 2050 and food production will have to increase by 70% to cover the nutritional needs of such a population [6], the task today is that of meeting the growing demand for food and feeds while using fewer resources. It has been estimated that the demand for cereals, for both food and feeds, will increase by about 50%, while it is expected that the demand for other food products, such as meat, dairy products, fish, vegetable oils, etc., will grow much faster [7].

Moreover, considering that livestock farming is one of the agricultural activities with the greatest environmental impact [8, 9] and that the production of animal products (poultry, pork and beef) will double [10], a radical change in current production models is already needed

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to correct inefficiencies, reduce food waste and encourage sustainable diets using alternative protein sources [11–13].

All these aspects, together with the rising cost of traditional feed ingredients, such as fishmeal and soya [14], stimulated researchers and feed manufacturers in the past decade to identify new strategies for the future feeding of farmed animals, and this has resulted in niche circular innovations.

The implementation of radical innovations is considered a driving force for the restructuring and development of a preventive and regenerative eco-industry that the new circular paradigms entail [15–17]. Indeed, according to the findings of recent studies [18, 19], CE cannot be achieved through the attempts of individuals but, on the contrary, involves systemic change, which tends to be radical rather than incremental [20, 21], in companies, industries, economies, norms, and behaviors.

This requires a complex and prolonged socio-technical transition that operates on multiple market levels [22–25] and depends on a multitude of factors, including the status and timing of innovation projects, the radical nature of the innovation, interactions between the regime and the niche, and windows of opportunity [26].

Considering that it was only in 2017 that the European Union authorized the use of some insect proteins in aquaculture feeds (Commission Regulation (EU) 2017/893) and in 2021 in feeds for poultry and pigs (Commission Regulation (EU) 2021/1372), it is only recently that the edible insect industry has started to attract considerable interest as a new circular business model [27].

This market, in fact, represents an innovation niche within the livestock feed sector, because of the potential of using insects as a "biotechnology" with the aim of "closing the loops" of the circular bioeconomy [28–33], which involves an emphasis on the use of value-added products derived from residues and waste, which are then repurposed into agricultural and other products [25].

The term circular bioeconomy was introduced by the European Commission, which defines it as: "the production of renewable biological resources and the conversion of these resources and waste streams into value-added products such as food, feed, bio-based products, and bioenergy. Sustainability and circularity must be at the center of the bioeconomy if it is to be successful. These objectives will promote the renewal of our industry, the modernization of our primary production systems and the protection of the environment and will help enhance biodiversity" [29].

In this context, many saprophagous insects—i.e., insects that can feed on decomposing organic matter—can be used in circular supply chains to recycle waste from the agro-food industry for use in animal feeds [34].

In 2019, the International Platform of Insects for Food and Feeds (IPIFF) estimated that up to 1.2 million tons of insect meal could be produced by 2025 [35, 36], which would reduce the importation of high-protein feed materials and the expansion of agricultural land outside the EU [37] and that up to 20 million tons of materials from the food industry could be completely recycled, with an additional million tons being suitable for technical applications.

However, despite the high potential and promising estimates, there are still several concerns about the feasibility of this market transition that follow Georgescu-Roegen's [38] thought that the economic process is entropic and requires a perpetual depletion of resources that must be offset by the forces of nature to maintain stability.

For this reason, the circular bioeconomy has often been criticized for being unlikely to increase the consumption of natural resources, including energy, water, and minerals, through the mere recycling of components and products [23, 25].

Furthermore, the market does not seem to be technically prepared for this transition [39] as selling prices of insect products continue to be excessive [40, 41] and vary widely, depending on the used insect species, the type of market for which the product is intended, operating costs per unit of water, electricity and labor, geographical regions, type of insect processing, level of mechanization and differences between rural and urban areas [42].

Moreover, studies have shown that most Western consumers are very reluctant to accept edible insects as food because of limited understanding and restricted avenues for engagement with this matter which is why the world of edible insects is still seen as a taboo [43].

Given the current lack of knowledge in this domain, this study draws upon existing literature to provide valuable insights into the challenges the market is confronted with in developing innovations that necessitate fundamental transformations, along with potential strategies to surmount these obstacles.

The purpose of this work is to present a research agenda to identify the potential relationships between the insect industry and the circular bioeconomy through a holistic analysis which includes economic, environmental, social, and legislative aspects [44–47].

The study is conducted based on the following research questions:

– What are the main factors hindering the insect industry's transition into a circular bioeconomy model?

– What future developments may be necessary to accompany the insect industry's toward closed-loop system?
– Which overarching themes are explored throughout the literature?

In this regard, a meta-synthesis was conducted through a systematic literature review using the PRISMA (http://prisma-statement.org/) selection system and a co-occurrence analysis on the main terms that emerged from the articles considered for the study to show what operational role insects could play in a circular bioeconomy context.

Through the identification of three main research themes that emerged from the co-occurrence map, the authors hereafter discuss the great potential of the industry to identify its future prospects.

Although the number of publications on insects has increased exponentially in recent years [48], to the best of the authors' knowledge this study is the first to discuss the main topics and issues related to circularity in the insect industry that have emerged from the literature through a systematic review approach, and thus to reveal the currently important issues related to organic waste management when using insects, to new ways of feeding animals through the use of alternative insect-derived protein sources, and to the social acceptability of direct and indirect entomophagy [49–53].

Despite the existing studies have undoubtedly contributed to the research on this topic, the aim of this paper is to offer a comprehensive conceptual framework that encapsulates all the economic, environmental, social and legal features of the sector [54].

Materials and methods

Meta-synthesis analysis

A meta-synthesis model is used to gain a comprehensive understanding of the current state of insect breeding in a circular bioeconomy context. This methodological approach can be easily used to interpret data and maximize learning from qualitative data, and it allows generalizable results that contribute to the existing literature to be reported and novel theories to be introduced [55].

By synthesizing the data from research papers, we can identify common themes, patterns, and insights that could provide a deeper understanding of the topic.

The use of a meta-synthesis model allows us to go beyond the findings of individual studies and to generate broader insights that could provide information for future research and policy development, while offering practical applications in the field of insect breeding within a circular bioeconomy framework. This method also provides an objective measure of the state of scientific research. It differs significantly from meta-analysis in that it employs an interpretive approach, as opposed to a deductive one, to understand and explain phenomena [56], and is useful to increase the transferability of findings to broader contexts, thereby addressing some of the limitations of qualitative research [57].

However, it must be considered that the methodology has its limitations, as the results depend on the quality of the considered studies and their heterogeneity, they may provide different results, depending on the weight assigned to the various studies, and may introduce bias and/or methodological errors.

The methodological framework of this work consists of two steps, which are carried out using rigorous and systematic methods to ensure replicability of the research and that a wide range of concepts is captured.

The first stage involves carrying out a structured and systematic literature search review, aiming to consolidate existing knowledge to guide the future research agenda on a topic in a logical and systematic way [58, 59].

This is aimed at minimizing bias by employing a rigorous methodology that included both quantitative and qualitative analyses [60]. Accordingly, knowledge about the phenomenon is managed in a systematic way, and the rationale behind these reviews follow clear, transparent, reproducible, and focused methodologies that allows communities of researchers and practitioners to be unified, thus providing sufficient evidence to inform policy and practice [58]. The review's findings will provide valuable information regarding current research deficiencies and potential avenues for future investigation concerning the insect market within the framework of a circular bioeconomy.

In the second stage, a co-occurrence analysis, which involved analyzing the terms that emerged from the titles and abstracts of the articles included in the paper, is performed. This allows terms to be aggregated according to the predominant topics in the literature and thus a meta-synthesis to be conducted.

Step 1: preferred reporting items for systematic review and meta analysis (PRISMA)

The present investigation is carried out utilizing published articles as components of analysis to investigate the literature and identify some of the aspects that influence the implementation of circularity in production systems that use insects.

A systematic and replicable technique is used, with the intention of identifying work that had explored the topic [61]. This research's operational implementation is conduct according to the Preferred Reporting Items for Systematic Review and Meta Analysis (PRISMA) method, which encompasses the well-defined steps of a systematic review, including eligibility criteria and relevant sources of information, exploration of strategies, selection process, results, and data synthesis [62].

Although initially designed for health sector assessments, the PRISMA protocol has demonstrated its applicability to other domains, such as marketing studies [63, 64].

To the best of the authors' knowledge, although the PRISMA process has already been applied to analyze certain aspects of entomophagy and social acceptance [65–67], it has here been applied for the first time to include studies from literature conducted to investigate the insect sector in a circular bioeconomy context.

By conducting a systematic literature review, which examines, synthesizes, and assesses the literature pertaining to a particular field of study to enhance the existing body of knowledge, this approach is select to offer a comprehensive account of the documented obstacles encountered during the adoption of circular economy business models in the insect market.

This would enable the derivation of sound conclusions and implications, while also addressing areas where further research is needed and promoting the development of new insights [68].

A comprehensive evaluation of the chosen scientific studies is conducted to assess their quality, with the aim of identifying the validity and reliability of their findings [69].

Because this review examines studies of a distinct nature, an integrative approach is opted for its investigation, as the studies' heterogeneous designs and outcomes disqualify quantitative analysis [70]. Hence, when significant discrepancies exist among studies about methodology, samples, outcome measures, or other pertinent aspects, employing traditional quantitative analyses, including meta-analyses, may become challenging or unsuitable.

On the other hand, the integrative methodology utilized aims to obtain a comprehensive comprehension of the results derived from the combined research, identifying themes, recurring patterns, or trends that emerge from the analysis of qualitative and quantitative data. The examination of the information sources was completed in October 2023.

Selection criteria

To furnish an all-encompassing and expansive overview of the topic, two major multidisciplinary databases, Scopus, and Web of Science (WoS) [71] were chosen, due to their comprehensiveness and dependability [72].

The selection process involved entering keywords into the "article title, abstract, and keywords" fields in Scopus and the "topic" field in Web of Science (WoS).

The investigation included all the possible combinations and variations of the following structured query: "circular economy" AND "insect*", while Boolean operators and wildcards were used in accordance with the purpose of this study. The Boolean operator "AND" was used to combine the circular economy and insect terms, and the asterisk character, "*", was employed to retrieve all the potential keyword variations.

The combined results of Scopus (215) and Web of Science (207) resulted in the return of 422 records from the systematic search.

Following the removal of 174 duplicates, 248 studies were found to meet the criteria adopted for the title and abstract screening. Afterwards, a total of n = 34 articles were excluded based on the screening criteria. In particular:

- Articles written in non-English language have been removed ($n = 3$);
- Only articles from peer-reviewed journals were included, while books ($n = 1$), book chapters ($n = 12$), editorials ($n = 6$), conference papers ($n = 10$), errata ($n = 1$), and notes ($n = 1$) were excluded as they lacked peer reviews.

No time restrictions were applied, as the searches attempted to cover all the peer-reviewed literature available so far on the topics [73].

Subsequently, while $n = 114$ articles were excluded after the screening of titles and abstracts while the potentially relevant articles ($n = 100$) were included, at the eligibility stage, in a full-text screening.

In this stage, the authors evaluated the appropriateness of every paper that satisfied the eligibility requirements by eliminating those that were irrelevant to the subject under investigation and including only those studies that demonstrated economic, social, environmental, and legislative determinants.

The following were the precise criteria for inclusion: (1) studies that has firmly established a correlation between CE and the insect market; (2) studies that investigated the legislative, environmental, economic, and social challenges that CE encountered in the insect market; and (3) studies that evaluated the positive aspects of CE in terms of economy, environment, and society in the insect market (Table 4). This inclusion criterion was developed considering the nascent stage of CE in this market to construct a knowledge agenda grounded in a more comprehensive body of research. The authors independently extracted the data, and any discrepancies among the assessors were addressed via internal deliberation until a consensus was achieved.

A detailed examination of the text content was conducted, for greater methodological rigor [74], to eliminate articles that did not meet the eligibility criteria for the review or were not directly relevant to the topic ($n = 50$).

Specifically, 8 articles were removed because their full texts were not retrieved, or articles for which it was not possible to access the text, 37 articles because they concerned technical analyses rather than economic, environmental, social and legal assessments, and 5 articles because they were not directly related to the insect sector, i.e., articles in which the topic of insects within a circular bioeconomy context, although present, is treated in a marginal way, and therefore not considered suitable in bringing useful information to the research objective.

Specifically, the following were excluded:

- Article related to the development of a model for municipal solid waste management ($n = 1$);
- Article on the nutritional aspects of introducing insects into the diet of ruminants ($n = 1$);
- Article related to incorporation of residues and manure on soil and feeding livestock with crop residues ($n = 1$);
- Article related to marine feed ingredients and production steps for sustainable food development ($n = 1$);
- Article on food design process through food innovation and digitalization in the food sector ($n = 1$).

After this comprehensive review, a final sample of 50 documents, which constituted a relevant and eligible set, was selected for the study. A PRISMA flowchart is shown in Fig. 1.

Step 2: co-occurrence analysis of the key words

The articles included in the systematic review were synthesized to perform the meta-synthesis and to construct the co-occurrence map of the most frequently appearing terms to identify themes, concepts, and relationships.

The software used is VOSviewer (http://www.vosviewer.com), version 1.6.19, which uses the VOS (Visualization of Similarities) mapping technique of conceptual points in a two-dimensional space [75]. The fundamental concept behind visualizing a bibliometric network is to facilitate the analysis of vast quantities of bibliographic data in a comparatively straightforward manner through the representation of the data's essential elements.

Bibliographic database files (Scopus and WoS) were supplied as input to VOSviewer to construct the co-occurrence network. The identification of the co-occurrences terms was based on textual data taken from the titles and abstracts, and a full count procedure was used that included only terms with at least five co-occurrences [75].

The visual representation was reported on the map, where the proximity of the concept points represented their relatedness, and the size of the concept points represented the frequency with which the concepts recurred in the text.

VOSviewer automatically designates clusters to represent closely related nodes in a network [76].

The process of identifying co-occurrence terms extracted from the textual data involves the generation of a set of noun phrases or generic terms that offer minimal information and must be omitted from the map to increase its utility.

To eliminate generic terms, VOSviewer assigns each term a relevance score. When terms have a high relevance score, they generally pertain to subjects addressed in the textual data. Conversely, terms that have a low relevance score are more general in nature and do not serve as representatives of any subject. The elimination of terms with low relevance scores allows for the prioritization of more specific and informative terms, while simultaneously excluding more general terms. 40% of terms are automatically excluded by the software due to their relevance score.

Nevertheless, it is imperative to emphasize that the purpose of bibliometric network visualization is not to provide definitive solutions to research inquiries; rather, it is to verify or refute the intuitions of researchers. When the judgment of researchers and the visualizations of bibliometric networks are congruent, they mutually reinforce one another; conversely, when they diverge, experts may be prompted to reassess their stance.

Results

PRISMA results

The results of the literature review indicated (Table 1) that all the articles were published within the past eight years, thus showing that this field of study is still in its infancy [77]. Therefore, new research is required, as the potential for exploration appears to be expanding.

Twenty-four of the 50 papers included in the analysis are articles, while the remaining 26 are reviews. The earliest publication that discussed this topic was an article by Borrello et al. [78], in which they illustrated the role of insects within the principles of a circular bioeconomy through the reuse of food substrates. The authors also assessed the methods and analysis tools used in the analyses.

We identified five homogenous groups of models and tools that were used in the case studies, which we defined as: (1) econometric models, including the Rasch model, Structural Equation Modeling (SEM), Seemingly

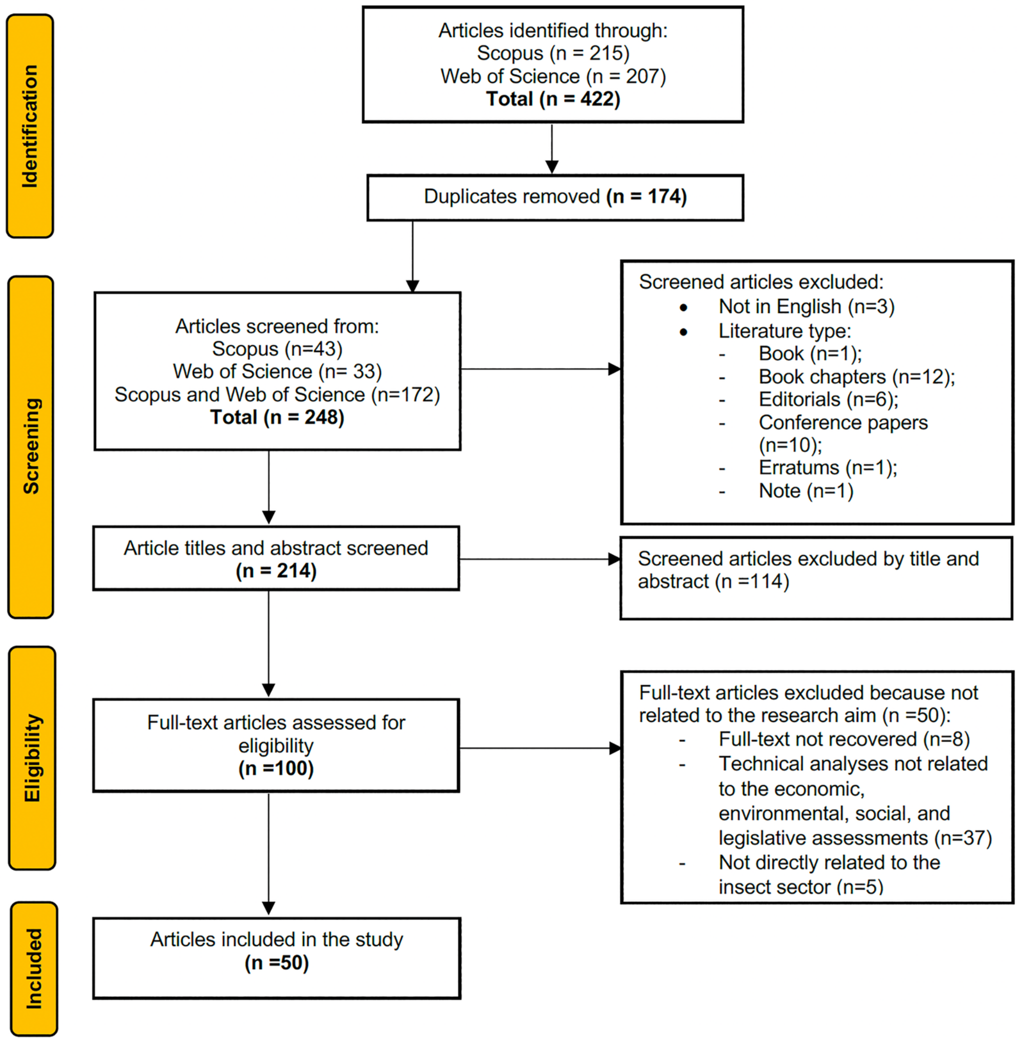

Fig. 1 PRISMA selection process

Table 1 Models and tools used in the papers

Econometric Models	Rasch Model [106]; Structural Equation Modeling (SEM) [145]; Seemingly Unrelated Regression [106]; Linear Regression Analysis [43, 102, 105]; Exploratory Factor Analysis (EFA) [43, 106, 135]
Life cycle	LCA (Life Cycle Assessment) [98, 111]; LCC (Life Cycle Cost) [87]; A-LCA (Attributional Life cycle Assessment) [86]; LCI (Life cycle Inventory) [100, 141]; Life Cycle Impact Assessment (LCIA) [100]**;** Sensitivity analysis [100]
Economic and financial models	Gross Margins [90]; Techno-Economic Assessment (TEA) [41]; Economic Surplus Model [97]; Economic Viability Indicators [95]; Return of investment [90]; Benefit–cost ratio [90]; Cost analysis [104]; Descriptive Statistics [128, 149]
Reviews	DiGiacomo and Leury [36]; Chia et al. [42]; Girotto and Piazza [80]; Pinotti and Ottoboni [81]; Ojha et al. [82]; Derler et al. [83]; Cammack et al. [84]; Ranjbari et al. [88]; Van Huis [89]; Girotto and Cossu [91]; Colombo et al. [92]; Gasco et al. [93]; Parolini et al. [96]; Sampathkumar et al. [101]; Maroušek et al. [103]; Kee et al. [107]; Cadinu et al. [109]; Van Huis et al. [116]; Mancini et al. [117]; Rumbos and Athanassiou [121]; Van Raamsdonk et al. [127]; Tanga et al. [142]; Gasco et al. [143]; Moruzzo et al. [144]; Pinotti et al. [145]; Moruzzo et al. [148]
Other models	Product safety [85]; Waste recovery hierarchy [85]; Process performance [85]; Decision Support Tool (DST) [110]; Geographic Information Systems (GISs) [98]; SWOT analysis [104]; Conceptual Map [78]; Delphi method [128]

Unrelated Regression, Linear Regression Analysis, and Exploratory Factor Analysis (EFA); (2) life cycle, including LCA (Life Cycle Assessment), LCC (Life Cycle Cost), A-LCA (Attributional Life cycle Assessment), LCI (Life cycle Inventory), Life Cycle Impact Assessment (LCIA), and Sensitivity analysis; (3) economic and financial models, including Gross Margins, Techno-Economic Assessment (TEA), Economic Surplus Model, Economic Viability Indicators, Return of investment, Benefit–cost ratio, Cost analysis and, Descriptive statistics; (4) reviews; and (5) other models, including Product safety, Waste recovery hierarchy, Process performance, Decision Support Tool (DST), and Geographic Information Systems (GISs), SWOT analysis, Conceptual map, and Delphi method. Table 1 shows the models that were employed in the studies included in the review.

Results of the co-occurrence analysis of the key words

A comprehensive analysis was conducted to identify the key terms in the titles and abstracts of the selected studies. Figure 2 visually presents the co-occurrence of these terms, which resulted in the formation of three distinct clusters. Each cluster, represented by a different color, highlights the main topics discussed in the literature. This clustering confirms the authors' classification that they had based on a thorough examination of the articles. The aggregated terms within each cluster emphasize the main themes explored in the research and provide a concise summary of the analyzed studies.

Therefore, on the basis of the clustering of the terms, we defined the following three emergent clusters: green, orange, and blue.

The key terms identified in the green cluster, which is also known as "Waste management by insects", are related to bioconversion processes carried out by insects on organic waste substrates. These terms also include "waste management", "biomass", "biotransformation", "biorefinery", "biofuel", "food", "diet", and "organic waste". Such studies referred to economic and environmental analyses and the evaluation of bioconversion processes of low-value organic substrates into high-value products such as food, feeds, bioenergy, biofertilizers, and by-products for different sectors. The topic was covered in 16 of the articles included in the review.

The orange cluster, defined as "Insect-based feeds", is easily traced to the use of insects as additives in animal diets; the main terms that emerged are the following: "circular economy", "sustainability", "animal feed", "sustainable development", "environmental impact", "waste disposal", "protein", "black soldier fly", "hermetia illucens",

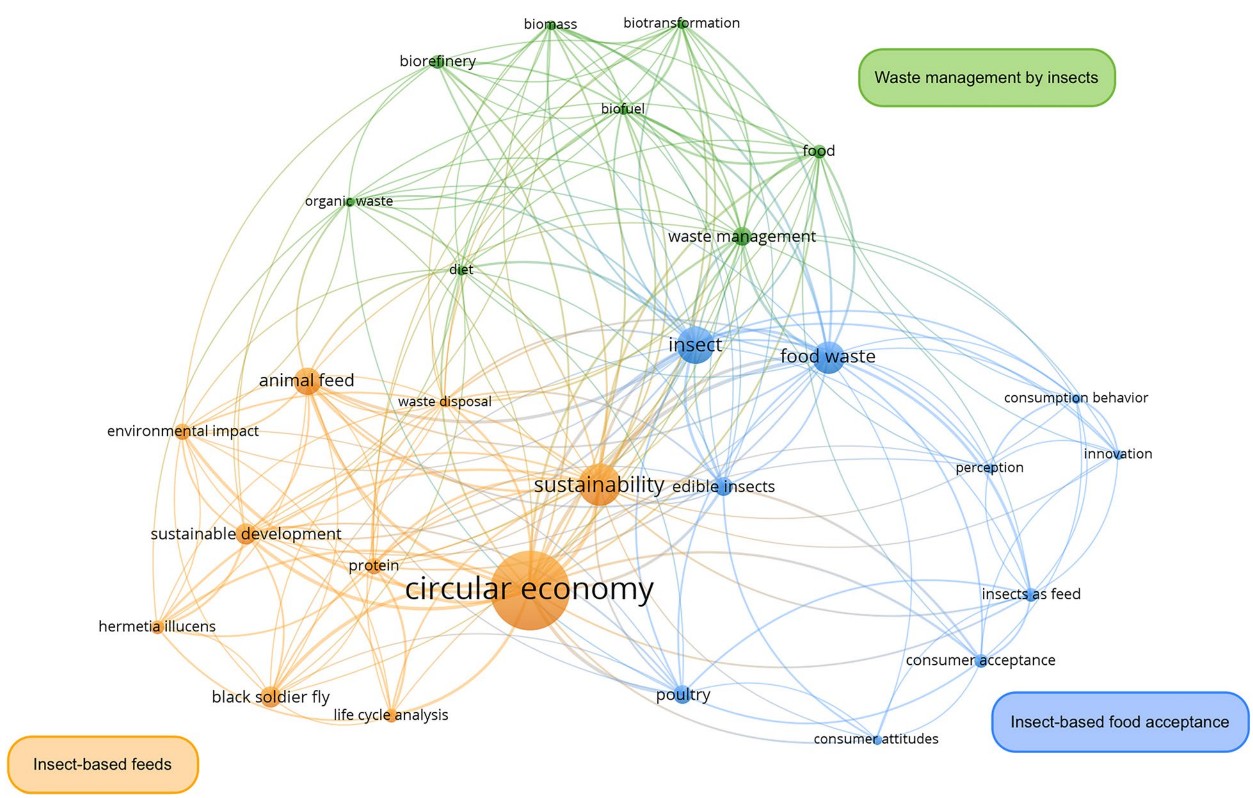

Fig. 2 Co-occurrence map

and "life cycle analysis". On the basis of the application of alternative protein sources in animal feeds in important sectors such as aquaculture, poultry, and pig farming, this topic was covered in 28 of the articles included in the review and this is the largest cluster.

Finally, the emerging terms in the blue cluster, "Insect-based food acceptance", can be traced back to the topic of insects for food use, and was identified by such terms as "insect", "food waste", "edible insect", "poultry", "insect as feed", "consumer acceptance", "consumer attitudes", "consumption behavior", "perception", and "innovation". This topic was covered in 10 of the articles included in the review. However, the fact remains that none of the themes can be considered separate or distinct.

A point-by-point analysis of each cluster is conducted in the following subsections according to the themes that emerged.

To have a clearer view of the considered papers, the authors have provided a detailed list of the articles included in the literature review, in which they have indicated the authors, and the year of publication (Table 2), and they have categorized them on the basis of the research areas according to an analysis of the topics of the selected documents (Table 3).

Table 3 The circular approach evidenced by the clusters

Research areas	***Circular approach***
Waste management by insects	• Upcycling processes to generate high-value products: - Micro and macro-nutrients [36, 42] - Biofuels [41, 84, 89, 91, 107] - Bio-lubricants [91] - Fertilizers [41, 84, 89, 91, 92, 107] - Pharmaceuticals [41, 84, 89, 107] - Cosmetics [89, 91] - Bioplastics [89, 91] • Benefits for smallholder farmers [42, 90, 95]
Insects-based feeds	• Upcycling processes to generate: - Alternative proteins [42, 85, 97, 109]
Insect-based food acceptance	• Co-design processes to generate: - Closed-loop systems [105]

Waste management by insects

The worldwide market for edible insects is expected to reach a volume of 730,000 tonnes by 2030 [79] due to the growing demand for huge quantities of insect biomass by industries to replace the currently used ingredients.

Among the possible solutions, insect-generated bioconversion represents an emerging tool to promote a circular bioeconomy [80] that is based on a cascading process of the biomass value pyramid.

Indeed, according to the findings of the literature review, from a given amount of relatively low-value biomass, it is possible to efficiently convert several tons of food waste into high-value products (upcycling) [81], such as protein and fat, in the form of food and feeds, and also into secondary products such as biodiesel [82–84].

This solution would reduce environmental impacts both upstream—through the use of organic waste matter as a food substrate for insects—and downstream—by using insects as substitutes for traditional feeds in the livestock and fish sectors, mainly as a protein alternative to fishmeal, fish oil, and soybean meal [42, 85], thereby generating innovative circular business models [86], as in the case of industrial symbiosis processes [87], which are aimed at maximizing socioeconomic benefits while increasing biomass use efficiency [88].

Intensive insect farming provides an opportunity to decompose significant quantities of organic waste while increasing the total insect biomass and producing a variety of products, including biofuels, fertilizers, and pharmaceuticals [41, 84, 89].

In addition, the material that remains after bioconversion processes (frass), i.e., a mixture of excrement, residues and exuviae from animal husbandry, is considered more suitable for application to soil as a fertilizer than, for example, raw manure, due to its lower moisture content and the presence of nutrients that could be

Table 2 Articles included in the review classified by research areas

Research areas	**Articles**
Waste management by insects	Girotto and Cossu [91]; Haq et al. [87]; Ojha et al. [82]; Rumbos and Athanassiou [121]; Suckling et al. [110]; Gold et al. [85]; Deler et al. [83]; Moruzzo et al. [148]; Cammack et al. [84]; Pinotti and Ottoboni [81]; Eskelinen et al. [43]; Ranjbari et al. [88]; Beesigamukama et al. [90]; Girotto and Piazza [80]; Beyers et al. [111]; Buccaro et al. [41]
Insect-based feeds	Borrello et al. [76]; Roffeis et al. [141]; van Raamsdonk et al. [127]; Chia et al. [42]; DiGiacomo and Leury [36]; Parolini et al. [96]; Abro et al. [97]; Gasco et al. [93]; Cadinu et al. [109]; Roffeis et al. [100]; Tanga et al. [142]; Jagtap et al. [98]; Spartano and Grasso [102]; Spartano and Grasso [99]; van Huis [89]; van Huis et al. [116]; Moruzzo et al. [144]; Rumbos and Athanassiou [121]; Tavares et al. [95]; Kee et al. [107]; Sampathkumar and Loo [101]; Colombo et al. [92]; Maroušek et al. [103]; Gasco et al. [143]; Barragán-Fonseca et al. [104]; Pinotti et al. [145]; Beyers et al. [111]; Buccaro et al. [41]
Insect-based food acceptance	Borrello et al. [144]; Moruzzo et al. [144]; Rumbos et al. [121]; Ouko et al. [128]; Mancini et al. [117]; Martins et al. [145]; Baldi et al. [106]; Piwowar et al. [135]; Dagevos and Taufik [105]; Mishyna et al. [149]

hazardous to the environment if over-applied as a fertilizer [84, 90].

According to van Huis [89], it is possible to extract such components as proteins, which can be used in food and feed applications, as well in certain technological applications such as bioplastics. Furthermore, chitin and chitosan can be used in biomaterial and biomedical applications, or even as fertilizers, as they trigger plant growth and induce plant defense, while fat can be used in animal feeds, cosmetics, bio-lubricants, or in biodiesel [91].

A further potential has been found for the use of insect fiber as a fertilizer and promoter of plant growth and development [92]. However, this biofertilizer is not currently able to cover the market needs and, therefore, can only be used in small-area applications.

Therefore, the advantages of bioconversion can be traced back to a reduction in waste management costs, a lower use of resources than other protein and fat productions, and a gain in value from the sale of insect-derived products, which is why using or valorizing food waste for animal feeds that include insects exemplifies perfectly how a system founded on circular bioeconomy principles can be built [93].

Insect-based feeds

Despite some studies [94] show that the production of insect meal does not seem to reduce environmental impact, according to the literature review and policy debate, the development of alternative insect-based feeds for intensive livestock systems shows a remarkable potential as it can address environmental and economic challenges through two key approaches. The first approach is focused on eco-efficiency [95] and has the aim of maximizing positive impacts and promoting circular production models using waste generated from food processing. The second approach centers around eco-effectiveness [96] and seeks to minimize negative impacts and promote sustainable production models.

Considering that feeds constitute a significant portion of the total production costs of livestock farms (where they can account for 60–70% of the total cost of production, as noted by Buccaro et al. [41]), this innovative approach could lead to a visible reduction in both environmental and economic costs within and beyond the production systems.

The scientific community is actively engaged in seeking solutions to integrate alternative food sources into the diets of farm animals [97, 98]. The objective of such solutions is to replace conventional nutrient sources and dismantle the current unsustainable production patterns predominantly witnessed for soybean meal [36, 96, 99] and fishmeal [97, 100, 101]. Currently, soybean meal, which is widely used because of its high protein content, dominates the feed market [96]. However, its cultivation and transportation entail significant environmental impacts, mainly related to land and water use [36]. Furthermore, the dramatic increase in the market price of soybean meal and fishmeal has become a critical aspect for the economic sustainability of the feed industry [41].

Therefore, reducing the dependency on such resource-intensive feed ingredients would not only reduce the environmental burden, but also allow feeds that would otherwise be waste to be used, increase animal welfare [102], and reduce reliance on European imports, for which the livestock sector is highly susceptible to trade distortions, scarcity, and price volatility on the global market [41].

Insects are already a part of the diet of many animals and fowl, including fish [101, 103, 104], poultry [41, 95–97], and swine [36], in many regions throughout the world, and increasingly in large-scale industrial facilities [36].

Considering that they are among the most promising alternatives for animal feeds, much of the work in the literature has in fact focused on the study of insects as feed additives, which, because of their excellent nutritional composition and digestibility [36, 42], can be used in such sectors as aquaculture, poultry, and pig farming [95].

In addition they are less impactful from the point of view of resources needed for farming and emissions downstream of production: they have short production cycles [105], low feed requirements, due to the high conversion ratio of such products as vegetables and fruit, grains and residues, manure, and animal remains [106], they require less land and water than conventional livestock systems [95, 107], and their annual ammonia-related [105] and greenhouse gas emissions are up to 100 times lower than those of conventional livestock [36, 108] for the same amount of protein produced [109].

Among the possible insect species that can be used in fish feeds, the Black Soldier Fly Larvae (BSFL) Hermetia illucens has been the most studied in the literature [90, 97, 104, 110, 111] and has been identified as the most versatile because of the variety of biological wastes that can be used for its rearing, automation, scalability, nutritional value, and because of circular and environmental aspects [103].

However, although the feeding of insects to livestock is aligned with a circular perspective in agricultural and food production systems [82], in terms of resource efficiency [110] and the utilization of by-products generated by insect farming [82], according to some studies, this link does not seem to be so direct. Indeed, agricultural by-products, which have a significant environmental impact, are currently used to feed insects [94].

Insect-based food acceptance

Customers co-creation, which refers to the proactive engagement of customers in the developmental processes of organizations, has been recognized as a viable approach for transferring customers knowledge to the enterprises [112, 113]. Co-design, an approach associated with the open innovation model [114], is a commonly employed term to delineate a more collaborative procedure wherein companies and consumers work together to test new business models to stimulate the radical creativity of small and medium enterprises [115].

As the idea of closed-loop systems involves increasingly active consumers through co-design processes [98], the social acceptance of entomophagy plays a crucial role and appears to be a key driver in the transition to a circular bioeconomy [105].

Although about one-third of the world's population in developing countries and parts of Japan and China already practice entomophagy [107], the Western world is still reluctant to do so and consumer acceptance is still low [116] due to unfamiliarity and a lack of experience in eating edible insects [105].

According to the studies included in the literature, the acceptance of entomophagy is greatly hindered by cultural concepts pertaining to food preferences, a lack of awareness of the potential environmental benefits of insects as food [99], psychological factors, such as food neophobia, which evokes disgust [107], and the association of insect consumption with the outbreak of diseases [36].

In recent years, numerous researchers [49, 50, 52, 117], have assessed the propensity of individuals to consume edible insects or products containing variable components thereof through "direct" and "indirect" entomophagy analyses.

However, different results have emerged that show that although disgust and neophobia negatively affect the acceptance and intentions of Western societies to consume food produced from insects [43], this effect seems to be less marked for insects used in animal feeds [102, 106].

Consumers with lower levels of food neophobia have in fact shown an increasing acceptance of animals, such as fish and chickens, fed on insects [102, 106], while they have shown a negative willingness to pay for direct entomophagy [117].

These results validate the conclusions drawn by Verbeke et al. [118], which suggest that consumer attitudes are generally positive regarding the use of insects in animal feed, particularly for fish and poultry, since these insects are found in their natural habitats [12]. Consequently, consumers view insects as natural foods that have the potential to improve animal welfare [119, 120].

The literature also presents numerous studies that provide mixed results on the awareness of the environmental benefits derived from eating insect foods as a determinant of acceptability [105, 116].

For example, the analysis carried out by Rumbos et al. [121] shows that individuals are aware of the environmental impacts of insect consumption, demonstrating a positive attitude and willingness to consume insect-fed fish. Instead, this result does not seem to have been confirmed by Dagevos and Taufik [105], who have found that sustainability-conscious consumers are not particularly more sensitive to insect consumption than those for whom sustainability plays a less important role in their lives.

The dietary regimes of consumers and familiarity with food preparation have also emerged as important factors in determining interest in and acceptance of entomophagy [117]. As far as this aspect is concerned, some studies [105, 116] have stated that, since consumers' attitudes can be influenced by the way products appear on the market, the development of highly processed insect-based foods in Western diets seems to be a market strategy that could promote the acceptance of these products in different forms, e.g., in powder form [106], creating tasty products that increase their palatability [116].

Finally, a lack of information is another element that limits social acceptance [107]. In this regard, given that consumers are the main drivers of an industry's development and that concerns about food safety and the appearance of insects have negative effects on their consumption [84], helping consumers to become aware and informed about these products may increase the likelihood that they will be less mistrustful and more likely to buy [107]. Therefore, reducing information asymmetries has been discussed as a strategic tool to push individuals toward the consumption of novel foods [106, 122].

The future research agenda

Developing alternative ways to meet food needs is now considered critical, and the use of insects represents a promising way of achieving this goal.

Indeed, while insect food and feeds are currently a niche segment in the EU [123], under Horizon Europe, they represent one of the most important research areas in the circular bioeconomy.

Although the findings presented so far seem to suggest that insects have a great potential in contributing to the development of circular business models [105] and that the market is expected to grow significantly, empirical evidence suggests that its large-scale application is hindered by technical, economic, logistical, and legislative barriers that prevent its full deployment.

This research agenda introduces an exploratory framework that situates the insect market within the framework of the circular bioeconomy. Thus, in contrast to previous studies that focused on individual aspects of this paradigm, it offers a new perspective on the current state of knowledge through a holistic exploration of the field; and it does so by employing for the first time two complementary methodologies—the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) and the co-occurrence analysis.

The findings derived from this research underscore the scarcity of empirical studies in the domain. Therefore, to assist stakeholders with their decision-making, a comprehensive quantitative–qualitative analysis of the potential repercussions of this market's transition to a circular model would be required. This could be accomplished, for instance, by employing multi-criteria analysis tools.

Moreover, while certain scholars [97, 106] argue for the incorporation of social factors, the existing research appears to have exhibited a distinct bias towards the economic system that yields the greatest environmental benefits, while disregarding the social aspects.

The results of this study validate the assertions made by multiple authors [77, 124, 125] regarding the significance of incorporating the social dimension and considering the sharing economy and participatory democratic decision-making as the primary subjects.

Given the limited amount of research available in this area, it becomes imperative to incorporate insights from other disciplines, including management, law, psychology, anthropology, and governance and cultural aspects, to address this concern. This may result in a substantial reassessment of existing theories and consequently give rise to a novel paradigm.

This research agenda therefore seeks to provide guidance on considerations that ought to be incorporated into the development of a comprehensive framework for the circular economy by means of a discourse on future research.

Future research on waste management by insects

Insect-mediated bioconversion presents a viable and sustainable strategy for waste management, concurrently generating valuable bioproducts.

To facilitate access to distribution networks and markets, however, requires substantial investments in knowledge, technologies, and automation of the entire production process [116, 126]. These investments are necessary to develop cost-effective and efficient large-scale production methods that also enhance product competitiveness, safety, quality, and environmental and financial sustainability [116, 126].

One potential resolution for commercial-scale production would involve the establishment of novel collaborative frameworks—with suppliers organizing groups to receive complimentary waste, distributors facilitating sales (including international sales), and feed mixers fulfilling biocharacterization and advisory services [36].

Moreover, the integration of insect farming into production chains would present additional prospects that would be advantageous to resource-poor farmers and smallholder farmers. Specifically, it would enable the latter to manage the organic waste generated on their farms in a sustainable manner [95], while the former would be able to increase their productivity [42].

This would generate prospects for subsequent investments that may result in the establishment of fresh employment opportunities and more sustainable food and agriculture systems, with a particular emphasis on small farms situated in low-income and middle-income nations [90].

Therefore, it is believed that solutions influenced by the circular bioeconomy have the potential to close nutrient cycles that were previously unrestricted, both internally within the farm via inter-farm cooperation and externally via the creation of novel value chains [86, 87].

Nevertheless, the absence of insect breeding facilities would pose a logistical obstacle for the entire supply chain, rendering closed-loop production processes unsustainable from an economic standpoint. While the environmental impact of processing and transporting insect proteins is comparatively less severe than that of conventional protein diets, it still contributes to emissions and energy consumption [111].

Furthermore, there is ongoing debate regarding the suitability of substrates for insect growth [42, 97], given that not all types of organic refuse are viable options for commercial reproduction [103].

Indeed, the safety of insect products is predominantly determined by the substrates utilized in their rearing. While certain substrates may contain contaminants that are degraded in the insect's intestines (e.g., pesticides and mycotoxins), others, such as heavy metals, may accrue [89].

While it is anticipated that non-edible foods, including fish and flesh, will be permitted as insect farming substrates soon, there remains a possibility that these materials may be hazardous due to the presence of objectionable substances [127].

An increasing body of scientific research supports the notion that insects can extract undesirable substances from products that are no longer suitable for human consumption. However, this evidence suggests that if the bioconversion of products containing packaging materials adheres to animal feeding standards, such substances can be incorporated into the diet of animals, thereby mitigating the risks associated with their presence [89].

Further research into insect-based bioconversion and selective breeding is thus required to permanently eliminate organic waste, minimize investment costs, maximize economic returns, and provide new avenues towards a circular bioeconomy, in order to maximize the capacity and potential benefits of this market.

Future research on insect-based feeds

Despite some insect-fed animal products having penetrated the European market, these products are still just considered a niche [107].

The idea of incorporating insects into animal feed is widely accepted by stakeholders representing diverse sectors associated with agriculture, such as the livestock and feed industry, government, consulting, financial, and research institutions, who are firmly convinced of the indispensability, attractiveness, and practicality of this ingredient [118].

The findings presented here are corroborated by the research conducted by Ouko et al. [128], which proposes that authorities in Kenya are in consensus concerning the possible utilization of BSF in aquaculture; thus, this suggests a considerable degree of acceptance.

Conversely, ruminant breeders harbor concerns regarding the utilization of insects as nutrition for their animals as they attribute this reluctance to a heightened perception of risks and a diminished perception of benefits, and therefore deem it impracticable or unlawful [118].

Indeed, although it is technically possible to include insects in commercial animal diets, many questions still remain related to legislative restrictions on the use of insect meal in livestock feeds [93, 101, 127]. Some of the concerns refer to the selection of insect species for feeding, their habitat, and dietary requirements [27, 103], the management of their waste, and the risk of potential ecosystem imbalance due to the possible escape of insects from farms [118, 129].

For example, in the European Union, insects destined for processed animal protein production are labeled as “farmed animals” [130] and are therefore subject to “feed ban” rules [131] and to animal nutrition regulations [130], which prohibit the use of various substrates, such as animal manure, catering waste, and meat and bone meal, as feeds [132].

Therefore, insects and their by-products intended for animal feeds are classified as “animal by-products”, which means that such animals and animal products are not intended for human consumption. This qualification imposes several obligations on producers, as outlined in Regulation (EU) No. 1069/2009 and Implementing Regulation (EU) No. 142/2011, which is also known as “EU animal by-products legislation”.

In addition, Regulation (EU) No. 1143/2014 limits the species of insects that can be used for breeding by establishing a list of “invasive alien species” to prevent the introduction into the environment of species that could threaten the biodiversity or surrounding ecosystems if accidentally released by breeding insects.

Thus, while waiting for industrial-scale production, it will be necessary to study new breeding substrates and evaluate the pros and cons of the potential biodegradation and biotransformation of manure by insects, the environmental risks and benefits, and the food safety [36, 133].

Future research on insect-based food acceptance

To be able to obtain a competitive edge during the shift from a linear to a circular economic system, both enterprises and consumers must participate in ongoing co-design interactions wherein customers actively contribute to the closed-loop systems [115, 134].

For this reason, according to scholars [105] recognizing the role of the consumer as the main promoter of economic models is crucial. Although the concept of circularity as a possible driver for consumer acceptance and the adoption of insect consumption have already been discussed and identified in many “insect-based food” articles [99, 102, 135], to the best of our knowledge, these topics still remain scientifically under-researched.

Indeed, although agreement has been reached in the research on the importance of consumer acceptance, the current studies on the human consumption of insects have often not focused specifically on circularity [105].

On the other hand, the social acceptance of entomophagy is one of the main drivers that can propel closed-loop systems forward, as the purchasing and consumption choices of insect-based foods can facilitate the adoption of policies that promote a circular bioeconomy [135].

According to the literature [106, 136, 137], one aspect that future research should address concerns the information asymmetry that currently exists between such an innovation industry and the consumer. Undoubtedly, the correlation between new technologies and food consumption has so far hindered the adoption of innovative products [138], as evidenced by the increasing consumer skepticism and risk perception [139]. The importance of information for food innovations has been demonstrated in several studies concerning aquaculture products [140], insects in feeds [137, 141–145], and insects as food [99, 136, 146–149]. Such information could reassure consumers about the safety and sustainability of the production process.

Conclusion

In spite of still being a niche market, insects appear to be a promising component of a future circular bioeconomy.

The research objective of this paper was to identify the relationship between the insect industry and the circular bioeconomy, and the potential benefits and lacks to present useful implications for the insect breeding industry and policymakers.

Although the number of specific studies that emerged from the review seems to be limited as a relatively recent topic, a multitude of challenges concerning operations and regulations appear to be emerging.

Given that political strategies play a role in establishing implicit social norms and values that can manifest themselves in innovative endeavors that serve as socio-technical visions of the ideal future, policymakers could facilitate market access to and the international trade of insect products by developing harmonized standards and regulations.

Further socio-technical research will be required to develop products that facilitate the integration of insects into large-scale production, methods of rearing insects on organic substrates to ensure product safety, and selective breeding techniques to maximize the capacity and potential of this sector. This approach would result in reduced investment expenses, increased economic returns, and market prices that are equitable and competitive.

More efforts will therefore be necessary from institutions and research regarding the adoption of new technologies or concepts by farmers, access to information and awareness-raising, anticipated impacts on the economic and environmental performance of their farming activities, uncertainties surrounding technological adaptations, economic investments, and social and market acceptance.

Moreover, there are still some concerns about the sustainability of certain aspects, such as the possibility of completely replacing feed products with alternative products to significantly reduce environmental impacts. In fact, the use of insects in feeds is limited to additives rather than complete diet replacement because direct substitutions are not always possible in complex diet formulations if the diets are to remain balanced.

Furthermore, scholars could place more emphasis on establishing new supply chains to support entrepreneurs in finding solutions that can address logistical challenges to experiment with more efficient production scales in the insect industry, which may increase in accessibility and competitiveness.

As a limited awareness of the circular economy concept and the potential of insect-based food have been observed among stakeholders, studies should be directed toward analyzing integrated models of extended insect supply chains from a systematic perspective. Therefore, the development of circular systems is deemed to necessitate an interdisciplinary approach, both about the acquisition of knowledge and the implementation of business models. These studies could shed light on the full potential of insect-based food as a sustainable and circular food system solution.

Furthermore, considering the undeniable emphasis on the environmental and economic aspects within the discourse surrounding the circular bioeconomy, it would seem prudent to regard the social aspect as a strategic leverage point.

By focusing on these areas, policymakers, researchers, and stakeholders could work collaboratively to ensure further research and development of technologies to accelerate the integration of insect-based food into circular food systems, enabling a more sustainable and resource-efficient future, while also fostering increased acceptance and understanding of the benefits of insect-based food for both consumers and industry stakeholders.

Furthermore, it has been hypothesized that consumer participation in co-design activities would also increase the likelihood that stakeholders could access and assimilate consumer knowledge, thereby diversifying their knowledge base and bolstering the capacity to generate revolutionary new concepts and to establish a common vernacular.

About that, to integrate technical and technological knowledge with insights from the social sciences, future research should strive to enrich its theoretical framework with diverse perspectives and areas of knowledge, paying particular attention to the relationships between them.

An additional aspect that merits scrutiny pertains to the practical viability of circular bioeconomy frameworks. The present interpretation, in fact, contradicts certain economic theories that contend the acceleration of economic growth would result from the expansion of renewable resource-based activities. For this reason, subsequent investigations should prioritize cost–benefit analysis studies pertaining to tangible instances of circular business models.

Limitations

The current study suffers from some limitations. First, the search was limited to two databases, which, despite being deemed adequate and sufficient to achieve the research objectives, may have led to some relevant articles being omitted. Indeed, it is plausible that important research was disseminated through platforms other than Scopus and Web of Science. A further limitation of this research concerns the exclusive reliance on scientific articles as a source and neglecting all other types of documents. Furthermore, as with any systematic review, the potential publication bias in favor of positive or anticipated results and the use of different statistical and data collection methods may have led to some further limitations.

Moreover, notwithstanding the significance of the findings, a critical constraint pertains to the design of the review. Indeed, despite the systematic nature of the procedure, it is reasonable to presume that other groups of researchers might prioritize the details that were disregarded in this review if they were tasked with replicating this work.

An additional constraint pertains to the examination of co-occurrences. The subjective nature of the co-word analysis maps presented by VOSviewer should not be disregarded when interpreting them. Moreover, the reduction of textual data to a network consisting solely of term co-occurrences results in the loss of contextual information regarding those terms. The issue of information loss is especially problematic due to the difficulty in quantifying the extent of loss and the potential impact on the conclusions that can be derived from bibliometric network visualization.

Ultimately, it is unattainable to arrange nodes in a two-dimensional space in a manner that precisely reflects the kinship between each pair of nodes through distance. The extent to which distances reflect kinship is thus only approximate.

Appendix

See Table 4

Table 4 Summary of reviewed articles

Authors	Type of analysis	Key findings
Abro et al. [97]	Economic	This research assesses the potential socioeconomic advantages that Black Soldier Fly Larvae (BSFL) meal could offer the poultry industry in Kenya. Substituting 5–50% of conventional feed sources with BSFL meal may generate an economic benefit, according to the findings; therefore, increasing investments to promote BSFL meal may contribute to increased environmental, social, and economic sustainability
Baldi et al. [106]	Social	This research investigates the determinants that may influence the acceptability of insect-fed farmed fish. In addition to environmental attitude, the results indicate that sociodemographic variables also play a role in explaining product acceptance; specifically, younger, and male consumers are more likely to embrace the product. Furthermore, informed respondents exhibit a greater degree of acceptance
Barragán-Fonseca et al. [104]	Environmental, economic, and social	The economic and social benefits for local economies and small producers are discussed in the study. The findings suggest that the Black Soldier Fly has the potential to offer small producers an economically feasible food source, enabling them to make a positive contribution to the development of their local communities
Beesigamukama et al. [90]	Economic	The economic advantages of rearing Black Soldier Fly on spent brewery grains amended with sawdust, biochar, and chalk were investigated. The results illustrate the significance of insect farming within the framework of the circular economy and provide justification for potential future investments that would enhance the sustainability of food and agricultural systems, with a specific focus on small-scale producers operating in low- and middle-income nations
Beyers et al. [111]	Environmental and economic	To assess Black Soldier Fly production in response to various diets, including agricultural residues, the study conducted an LCA. Insect proteins exerted a more pronounced influence compared to soymeal or fishmeal proteins, as indicated by their elevated energy requirements and, in certain instances, support for agricultural product demands
Borrello et al. [78]	Environmental, social and legislative	A model is presented in the study that incorporates two revolutionary technological advancements, one of which pertains to the utilization of insects as animal feed. The outcomes delineate the primary obstacles that arise during the execution of novel circular supply chains through an analysis of their environmental, social, and legislative distinctiveness
Borrello et al. [144]	Social	Consumers' propensity to participate in closed-loop systems designed to reduce food waste using a profoundly innovative technology—insects as feed—was evaluated in the study. The findings indicate that there is a proportion of the sample that is enthusiastic about advancing the circular economy transition

Table 4 (continued)

Authors	Type of analysis	Key findings
Buccaro et al. [41]	Economic	The objective of this research endeavor is to assess the industrial viability and technological efficacy of a poultry feed manufacturing process that utilizes the pre-treated organic fraction of municipal solid waste as a substrate for the larval development of Hermetia illucens. The results indicate that it is not possible to classify the model as profitable, as its profitability is highly dependent on the economies of scale
Cadinu et al. [109]	Environmental and economic	The review focuses on the three insect species that look set to positively influence aquaculture, which is the activity currently most sensitive to circularity and sustainability innovation. Finally, the environmental and economic challenges that the sector will face are appropriately highlighted
Cammack et al. [84]	Environmental	This analysis centers on the potential contribution of the Black Soldier Fly to the management of the substantial quantities of manure and unprocessed materials that may be generated. Furthermore, there is speculation regarding the potential of other species, such as the housefly and the lesser mealworm, to contribute significantly to the management of animal manure and the production of valuable products
Chia et al. [42]	Environmental, economic, and social	Insect farming to encourage inclusive activities among smallholder farmers in the agribusiness value chain is examined in the review. The results indicate that inclusive business models that rely on insects may aid in the resolution of socioeconomic and environmental issues in developing nations
Colombo et al. [92]	Environmental and economic	The aim of this review is to provide an overview of the function of blue food production, and to analyze the potential of this framework to enhance the resilience and sustainability of aquaculture. The findings indicate that insects would contribute to a sustainable future in this context
Dagevos and Taufik [105]	Social	The purpose of this research is to assess whether consumers' inclination toward circularity serves as a defining feature in their willingness to consume insects. The findings indicate that individuals who prioritize sustainability do not exhibit a heightened sensitivity towards the consumption of insects, and that processed insect-based foods to be more palatable in comparison to consuming whole insects
Derler et al. [83]	Environmental	A comprehensive summary of the by-products that have been or may be administered to Tenebrio molitor is presented in the article. Diverse viewpoints are offered by the results, which may contribute to the development of circular and environmental resource-efficient food and feed production
DiGiacomo and Leury [36]	Environmental and economic	The prospective use of insect-derived proteins as a dietary source for the Australian swine industry is the focus of the review. The outcomes illustrate environmentally sustainable practices that facilitate the production of sustenance and fertilizer
Eskelinen et al. [43]	Social	The research offers insights into the determinants that influence societal adoption of novel protein-based food sources, as well as feed and fertilizers derived from organic refuse. The results indicate that males are more receptive to insect-derived protein products
Gasco et al. [93]	Environmental and legislative	Regulations that govern and restrict the mass production and applications of insects are also discussed, as is the potential use of insects to valorize food refuse for animal feed
Gasco et al. [143]	Environmental	The article examines the potential of insect excrement as a viable fertilizer, noting its reduced environmental impact compared to synthetic fertilizers. The findings suggest that the insect market makes a significant contribution within the framework of a circular bioeconomy
Girotto and Cossu [91]	Environmental, economic, and legislative	An overview of the potentially advantageous applications of worms and insects in waste management is presented in this article. According to the results, existing legislation is incapable of granting approval to the essential protocols required to guarantee a secure and methodically implemented implementation of the emerging invertebrate biorefinery economy
Girotto and Piazza [80]	Legislative	The occasion centers around the utilization of food refuse as a valuable biomass resource to support the development of novel nutrients, including insects. The findings reveal deficiencies and constraints within the legislative structure
Gold et al. [85]	Environmental and economic	This research undertakes a methodical evaluation of Black Soldier Fly Larvae treatment substrates for the modernization of a plant in Nairobi. The results indicate that most organic waste is currently unsuitable for plant upgrades due to inorganic contamination and the absence of cost-effective waste collection services

Table 4 (continued)

Authors	Type of analysis	Key findings
Haq et al. [87]	Environmental and economic	In this study, several new markets were evaluated, including insect farms for the development of a potential industrial symbiosis architecture in Finland. The results indicate that this symbiosis is expected to achieve a value of 14.65% and reduce costs by 6.8%, which will enable these companies to meet the requirements of the circular economy and sustainability
Jagtap et al. [98]	Environmental and economic	The larvae of the black soldier fly are identified as a bioreactor in this study; they transform the preponderance of food debris into high-value feed materials
Kee et al. [107]	Environmental	This article provides an overview of the current state of the insect industry, including organic waste potential for bioconversion and insect biorefinery
Mancini et al. [117]	Social	The review examines the prospective developments in the insect market. The findings indicate that this industry is experiencing growth, and its prospects are contingent not only on the demand for food but also for feed, which is anticipated to have substantial demand in the future
Maroušek et al. [103]	Environmental and economic	This review provides an analysis of the commercial implications of incorporating insects into intensive aquaculture feeding practices. The primary results demonstrate that Black Soldier Fly Larvae exhibit the greatest adaptability about the range of organic waste that can be utilized, automation and scalability, nutritional composition, as well as circular and environmental implications
Martins et al. [145]	Social	The study's primary aim is to ascertain the determinants that impact consumer inclination towards attempt new dishes. The findings indicate that insect-based foods are a novel food category for Europeans, and that their nutritional profile, reduced ecological imprint, and high social acceptability in comparison to other protein sources are the driving forces behind this trend. Furthermore, culture, individual and social beliefs, the tactile, olfactory, visual, and gustatory senses influence the consumption of insect-based foods
Mishyna et al. [149]	Social	The purpose of the study is to determine the attitudes and intentions regarding the production and consumption of edible insects for human consumption on a local, industrial, and household level. Respondents exhibited a greater preference for environmental, economic, expert support, and safety considerations, while industrial insect production was deemed more economically viable. Domestic production was hindered by a lack of knowledge and information, economic considerations, inconvenience, and economic factors
Moruzzo et al. [144]	Environmental and legislative	The research examines the market potential of insects with respect to the Sustainable Development Goals. Future utilization of edible insects will necessitate the establishment of knowledge-sharing networks, investment in interdisciplinary research, and the formulation of sustainable policies, according to the findings
Moruzzo et al. [148]	Environmental, social, and legislative	The article investigates the viability of incorporating Tenebrio Molitor into circular production systems through an analysis of its implementation and suitability across various industries, including agriculture and food. Notwithstanding the insect's remarkable adaptability and potential as a substitute nutrient source, the findings suggest that numerous legislative and behavioral obstacles continue to impede its acceptance and implementation
Ojha et al. [82]	Environmental and economic	By amalgamating the manufacturing of edible insects with the recovery of food refuse, this document offers a compelling solution to the challenge of closing the food value chain
Ouko et al. [128]	Social	The aim of this research was to ascertain the perceived advantages and disadvantages of Black Soldier Fly Larvae (BSFL) meal in aquaculture, as well as the factors that influence the endorsement of BSFL in fish production. The results indicate that stakeholders are in accord and have a high degree of acceptance regarding the necessity of using BSFL as a protein constituent in aquaculture. Policy, health inspection, feed safety, environmental influences, and fish quality were deemed the most crucial factors
Parolini et al. [96]	Environmental	Concerning the usability, applicability, and efficacy of earthworms as an alternative protein feed in aquaculture and poultry production, the manuscript provides a synopsis. Because of the findings, mealworm incorporation into animal nutrition would enhance environmental sustainability by facilitating high-quality final products while maintaining efficient production
Pinotti and Ottoboni [81]	Environmental	The review provides an examination of research that has assessed the bioconversion of various substrates by insects. Insects have the capacity to contribute to a circular economy by converting both low-quality and high-quality organic matter into high-quality biomass, according to key findings

Table 4 (continued)

Authors	Type of analysis	Key findings
Pinotti et al. [145]	Environmental	The findings of this research suggest that insects have the potential to impact the quality of meat, particularly about specific constituents like lipid content and overall quality. Alternative feeds are anticipated to be utilized more frequently on a global scale to substitute conventional feeds, thereby mitigating their ecological footprint
Piwowar et al. [135]	Social	The purpose of the research is to assess the level of consumer reception towards novel food items, including edible insects. According to the findings, participants' intentions to choose insect-based food products increased significantly after they were informed of the environmental and circular advantages of entomophagy
Ranjbari et al. [88]	Environmental and economic	This bibliometric analysis aims to provide a complete map of the body of knowledge present in the world literature on biomass and organic waste from a circular economy perspective. Among the results emerges the role of the insect biorefinery of waste management in the CE framework
Roffeis et al. [141]	Environmental	An examination and comparison of the process performance of various insect-based feed production systems utilizing Musca domestica and Hermetia illucens cultivated on distinct substrates are the objectives of this study. Despite having the highest conversion efficiency, Hermetia Illucens demonstrated significantly greater inputs in terms of labor, fossil fuel consumption, and effluent generation
Roffeis et al. [100])	Environmental and economic	This research examines the ecological impact of insect-based feeds (IBF) manufacturing. Research has shown that the effects of IBFs are predominantly influenced by the environmental pressures imposed on breeding substrates and breeding techniques. Additionally, an examination in contrast to conventional feed brought to light the ecological drawbacks associated with ongoing IBF production initiatives
Rumbos and Athanassiou [121]	Environmental and economic	The purpose of this article is to provide an overview of the current research status concerning insects as a source of sustenance and nutrition, as well as other exploitation-related aspects of insect farming
Sampathkumar et al. [101]	Environmental, economic, and legislative	The purpose of this review is to present a thorough examination of the potential for industrial food waste to be converted into aquaculture feed as a sustainable alternative to fishmeal. This will be achieved by analyzing current regulations pertaining to waste utilization in aquaculture, public opinion, and the outlook for the future of food waste conversion into aquaculture feed
Spartano and Grasso [102]	Social	The research examines the factors that influence individuals' willingness to attempt (WTT) and pay (WTP) for eggs produced by chickens fed insects, as well as the determinants of these behaviors. The results indicate that revulsion is a barrier to consumption and that most consumers are prepared to attempt and pay for the product
Spartano and Grasso [99]	Social	The study aims to explore consumer attitudes and perceptions towards insect-fed eggs and the factors that influence intentions to consume and purchase the product. The results indicate that price and disgust towards insects as feed are the main barriers, while improved welfare standards and information on benefits are the main drivers
Suckling et al. [110]	Economic	A case study utilizing Hermetia Illucens in compact bioconversion units is presented in this work. Three business models are assessed, two of which rely on desiccated Black Soldier Fly meal utilized as aquaculture feed and one of which utilizes live Black Soldier Fly Larvae to nourish local poultry. The live BSFL business model has demonstrated the greatest resilience and the highest profit margins
Tanga et al. [142]	Environmental, economic, and legislative	This review provides an analysis of recent research trends pertaining to farmed insect species and critical substrates, a map of commercial enterprises, nutritional values of insects, processing techniques, marketing strategies, regulatory framework, and insights gained from insect farming. The results offer significant insights into the economic and technical aspects and establish a distinct trajectory for expanding the use of these technologies in the pursuit of a circular food economy
Tavares et al. [95]	Economic	The objective of this study is to assess the economic viability of incorporating Tenebrio Molitor feed into the broiler chicken diet. The findings suggest that the incorporation of insect meal into poultry diets led to a proportional increase in feed costs. However, the gross margin experienced a significant decline of 93% to 98% when this ingredient was included in diets varying from 4 to 12%, in comparison to the control diet

Table 4 (continued)

Authors	Type of analysis	Key findings
van Huis [89]	Social	The review examines the insect industry, which is undergoing accelerated development despite approaching numerous obstacles. The results indicate that these issues can solely be resolved through the collaborative efforts of all relevant parties
van Huis et al. [116]	Environmental, economic, social, and legislative	The article covers a variety of subjects pertaining to the production of insects for consumption and as feed, including environmental impact, facility design, substrates, insect welfare and the assessment of regulatory frameworks. In addition, consumer perceptions of food products derived from insects and the sector's challenges and policy are discussed
Van Phl et al. [86]	Environmental	The objective of this study is to assess the environmental performance of the symbiosis model in comparison to a no-symbiosis model, as well as to compare the environmental impacts associated with the production of insect meal and insect oil in comparison to their respective alternatives. The outcomes demonstrate that the implementation of the symbiosis model substantially alters the environmental footprint by 83% and CO_2 emissions and fossil resource depletion are reduced, respectively. Insect meal and insect oil produced using the symbiosis model were also shown to be more sustainable, with CO_2 emissions reduced by a minimum of 55% and 83%, respectively, when compared to the best alternatives
van Raamsdonk et al. [127]	Environmental and legislative	The research paper provides a comprehensive examination of various facets including feed safety, environmental concerns, efficiency, and insect identity detection. Additionally, this paper addresses the legal limitations that pertain to the safety of insect-based foods in terms of contaminants, heavy metals, mycotoxins, pesticides, and pathogens

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Author contributions
MH: conceptualization, data curation, formal analysis, investigation, methodology, software, writing—original draft and writing—review and editing. MD: conceptualization, methodology, funding acquisition, project administration, supervision, validation and visualization. GDV: conceptualization, methodology, writing—original draft, writing—review and editing, supervision, validation, and visualization. All authors read and approved the final manuscript.

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