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Toward a circular economy in Italian agri-food: upstream partners in insect biorefineries

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Abstract

The insect biorefinery (IB) is central to recycling nutrients from food losses and waste (FLW) in an emerging circular bioeconomy approach. The sustainable leadership of the European insect industry and its integration into the bioeconomy depend on implementing symbiotic production models through site selection and partnerships. Only 8 studies, including 3 in the EU, have examined stakeholder acceptance. This pilot study is the first to focus on potential upstream symbiosis partners (USPs) in the EU, examining the factors that influence the willingness of potential USPs in suitable Italian locations to adopt IB. Preliminary analyses identified a final sample of 31 respondents who completed an online-survey divided into four sections. After data elaboration, a principal component analysis was conducted, considering 27 questions and their correlations with the first two principal components. The analysis revealed that the presence of internal research and development within the company, along with the company's role in the supply chain and the seasonality of production, had a minor influence on explaining the variance of the data. Interestingly, company size was negatively correlated with the willingness to become part of the insect-rearing supply chain or receive information about this technology. On the contrary, interest in innovative production and self-management of by-products were strongly related. Finally, funding opportunities could positively influence both the Italian and EU contexts, encouraging innovative practices among small and medium-sized enterprises. In contrast, barriers to implementing insect farming include misinformation, anticipated negative media impacts on branding, and resistance to changing by-product management practices. This pilot study serves as a foundational exploration, providing insights into the acceptability of insect farming among potential USPs and offers valuable insights for future studies, thereby shaping the discourse on the acceptability and integration of insect farming within the circular bioeconomy.

Keywords: Insect biorefinery, Upstream stakeholder acceptability, Insect farming, Circular economy, By-products upcycling

Introduction

Background

Population growth worldwide has caused several negative effects on society, such as increasing demand for food and the related production of large amounts of waste and by-products (Alam and Kafeel 2013; Srivastava et al. 2023). There is a broad consensus that reducing Food Loss and Waste (FLW) is imperative, leading to the formulation of numerous action plans in recent years (Flanagan et al. 2019). In a world with finite resources, FLW must be considered a source of secondary raw materials. Therefore, virtuous downstream mitigation strategies must be implemented to prevent landfilling and open dumping and prevent waste material from being misused (Chaboud and Daviron 2017). Downstream mitigation strategies, particularly FLW biorefining, are explored within the circular economy framework, converting biomass into marketable products such as biogas, compost, and nutrients (Alibardi et al. 2020). Insect Biorefinery (IB) is a novel circular bioeconomy strategy, utilizing insects such as the yellow mealworm (*Tenebrio molitor* L.) and black soldier fly (*Hermetia illucens* L., BSF) to valorize FLW into protein, fat, and other valuable derivatives (Kee et al. 2023). The European insect industry, a leader in innovation and technology, lacks comprehensive studies on the socio-environmental sustainability of IB within a circular bioeconomy (Derrien and Boccuni 2018; Smetana et al. 2023). A 2020 study highlighted the role of European and U.S. insect companies in advancing the bioeconomy by offering an eco-friendly protein alternative to traditional livestock. However, these companies need to address food waste issues, particularly the underutilization of FLW as a larval feedstock (Skrivervik 2020). One could argue that the European insect industry's capacity to implement symbiotic production models is crucial for retaining its leadership and fostering a closer connection with the bioeconomy. This entails identifying suitable production sites, considering their proximity to agro-industrial establishments (Fiorillo et al. 2023) and symbiosis partners (Hein et al. 2017), as well as actors who are directly involved or intend to be involved in a material/energy exchange. As innovation systems are a collective effort, there is much literature suggesting the participation of stakeholders from industry, civil society, government, and academia (i.e., the Quadruple Helix model) (Carayannis and Campbell 2010). To gain a nuanced understanding of system dynamics, Freeman's stakeholder theory (Parmar et al. 2010) allows for the categorization of stakeholders as either upstream or downstream. Upstream stakeholders can be defined as those involved in the supply side of the chain, such as suppliers and manufacturers, while downstream stakeholders are those on the demand side, including retailers and customers.

It is therefore urgent to consider acceptance among different stakeholders when looking at insects as a possible means of reducing food waste. Without social acceptance, cultivating insects and their products is unlikely to occur with any intention (Skrivervik 2020; Kröger et al. 2022).

Literature review and problem statement

Even though it has been pointed out that understanding and researching the acceptability of insect products and productions is a big issue that needs to be solved before large-scale insect production can happen, there are relatively few studies on this subject indexed in SCOPUS. These limitations encompass several key points. According to Sogari et al. (2019, 2023), most studies look at how consumers feel about eating or feeding insects. Also, as far as the authors know, only eight studies have looked at how symbiosis partners and Quadruple Helix stakeholders other than consumers feel about insect food or feed. Table 1 displays these studies and highlights their scope in studying stakeholders' acceptance across different investigated regional scenarios.

Within EU countries, the most comprehensive study was conducted in 2015 among downstream stakeholders only (Verbeke et al. 2015). Two studies published in 2023 highlight the increasing interest and research efforts to investigate acceptance among EU consumers and livestock farmers as downstream stakeholders (Table 1). The literature review revealed a significant need for more focus and understanding of the determinants of potential Upstream Symbiosis Partners (USPs) for IB in both developed and developing countries.

The literature on entrepreneurial ecosystems emphasizes the recognition of IB as aligned with circular economy principles, highlighting the resource efficiency and nutrient recycling inherent in this approach (Dung et al. 2014). However, the literature also underscores that more data is needed to guide strategies for the implementation of insect-based symbiotic production models. This emphasizes the importance of understanding the challenges and opportunities associated with the acceptance and production of insect-based products (Lichtenstein and Lyons 2006). This underscores the gap between existing knowledge and practical implementation and highlights the need for further research and practical insights.

Objectives

This study adopted a comprehensive framework to assess the factors driving a sample of potential Italian USPs in their decision-making process regarding the adoption of IB.

The specific objectives of the framework include: (1) to assess USPs' awareness and motivation to adopt IB and (2) to identify and quantify the importance of the factors that influence their willingness to adopt IB.

Materials and methods

Study area and sample selection

The study was conducted in seven provinces in northern Italy, namely Asti and Alessandria (Piedmont region), Pavia (Lombardy region) Parma and Piacenza (Emilia Romagna Region; L-P region), Trento and Bolzano (Trentino-Alto Adige region; T region) (Fig. 1).

These Italian provinces were selected due to their agro-industrial character and the associated large production of FLW, which makes them excellent candidate for the establishment of insect farms (Fiorillo et al. 2023; Agnoletti and Biasi 2013). Various crops such as cereals, soybeans, fruits, vegetables, grapes, and other fruit trees are grown in these regions. Detailed research was conducted to identify the companies to be interviewed. Based on findings of previous research on larvae diet (Meneguz et al. 2018, Spanghers et al. 2017), the research team used specific ATECO (ATtività ECOnomiche; ENG: economic activities) codes, which represents the classification of economic activities according to ISTAT (Istituto nazionale di STATistica; ENG: the Italian National Institute of Statistics). The companies and their associated ATECO codes were selected on the basis on EU Regulation 893/2017 and 1104/2022, which list the by-products that can be used as ingredients for the insect's diet (European Commission 2017; European Commission 2022). The research team excluded companies that were unable to provide unpackaged vegetal products, which otherwise have meant a significant loss of time in

Table 1 Published articles dealing with the acceptability of insect production and insect products by stakeholders other than consumers indexed by SCOPUS corresponding to the search query TITLE-ABS-KEY ("acceptability" OR "acceptance") AND ("insect farming" OR "insect-based") AND (farmer*). Date of SCOPUS search: 16 September 2023

Title	Quadruple Helix stakeholders	Streams	Scenario	Reference
Smallholder farmers' knowledge and willingness to pay for insect-based feeds in Kenya	Livestock Farmers (industry)	Downstream	Kenya, Africa	Chia et al. (2020)
Farmers' perceptions of commercial insect-based feed for sustainable livestock production in Kenya	Livestock farmers (industry)	Downstream	Kenya, Africa	Okello et al. (2021)
Stakeholders' perspectives on the use of black soldier fly larvae as an alternative sustainable feed ingredient in aquaculture, Kenya	Livestock farmers (industry)	Downstream	Kenya, Africa	Ouko Okoth et al. (2022)
Determinants of small-scale farmers' intention to adopt insect farming for animal feed in Colombia	Livestock farmers (industry)	Downstream	Colombia, South America	Diaz et al. (2021)
Insects in animal feed: Acceptance and its determinants among farmers, agriculture sector stakeholders and citizens	Consumers (civil society); Research institutions (academia, industry); Livestock farmers (industry); Feed industries (industry); Food industries (industry); Consultancy (industry); Finance (industry); Government (government);	Downstream	Belgium, Europe	Verbeke et al. (2015)
Insect-based feed acceptance among consumers and farmers in Ireland: a pilot study	Consumers (civil society); Livestock farmers (industry)	Downstream	Ireland, Europe	Ranga et al. (2023)
Insect production as a novel alternative to livestock farming: exploring interest and willingness to adopt among German farmers	Livestock farmers (industry)	Downstream	Germany, Europe	Weinreis et al. (2023)
Review: recent advances in insect-based feeds: from animal farming to the acceptance of consumers and stakeholders	Consumers (civil society); Livestock farmers (industry)	Downstream	Europe	Sogari et al. (2023)

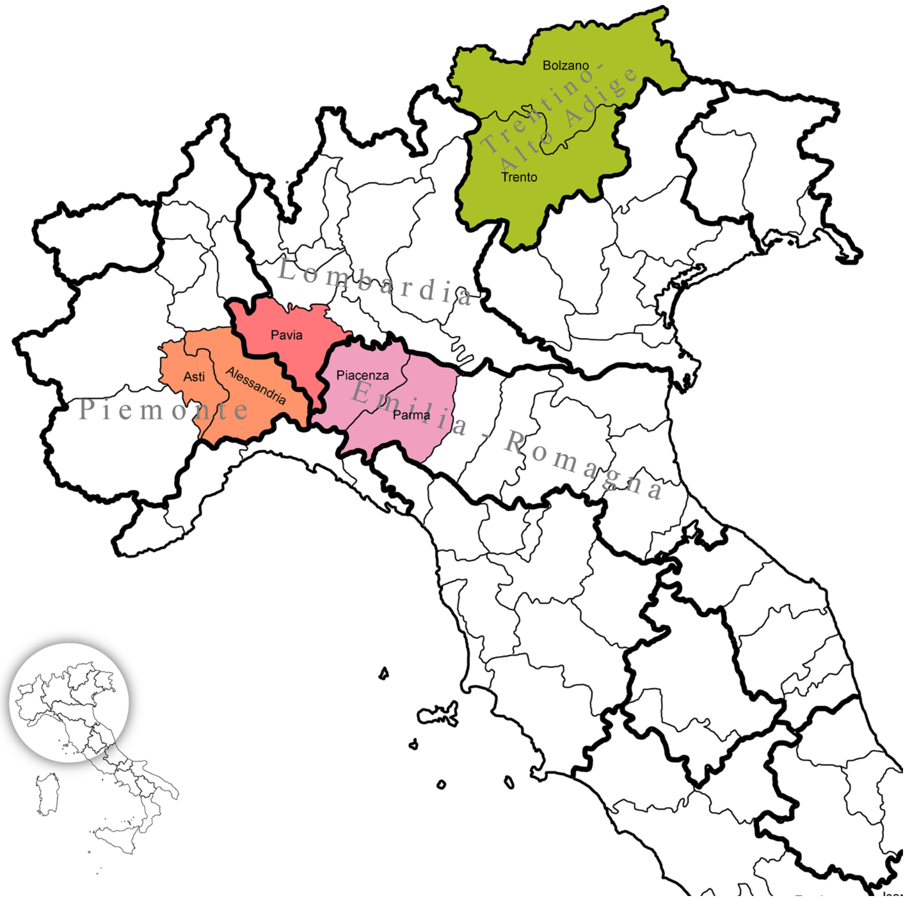

Fig. 1 Map showing the location of the Italian provinces involved in the study. Trento and Bolzano (Trentino-Alto Adige Region, T) are marked in green; Lombardy, Piedmont and Emilia Romagna Regions (L-P) are presented in red, orange and pink, respectively

IB feed preparation. The ATECO codes served as a filter in the AIDA database (Analisi Informatizzata delle Aziende Italiane 2023; ENG: Computerised Analysis of Italian Companies) a comprehensive database of Italian companies, to identify relevant local companies with active legal status as of February 24, 2023. The targeted ATECO codes covered a range of activities related to crop production, post-harvest activities, and the processing of fruits, vegetables, and related products (Table 2).

Out of 568 companies, 31 were selected based on their high influence, identified through a stakeholder analysis using the interest/influence matrix (Johnson and Scholes 1999; Park et al. 2017). This matrix classifies stakeholders according to two dimensions: their degree of influence (i.e., the company's ability to impact the industry or project outcomes) and their degree of interest (i.e., the company's focus on the topic under investigation), as reported in Fig. 2.

Since this is an empirical method, the potential interest of these stakeholders was inferred based on available data and preliminary observations, such as the company's past involvement in sustainability projects or public statements. The influence was determined using established criteria like heterogeneity of production and network and collaboration capacity (Boesso and Kumar 2009; Pan et al. 2012).

Table 2 List of the 18 targeted ATtività ECOnomiche (economical activities) ATECO codes

ATECO Code	Title
0111	Growing of cereals (except rice), grain legumes, and oil seeds
0112	Growing of rice
0113	Growing of vegetables and melons, roots, and tubers
0121	Growing of grapes
0124	Growing of pome fruits and stone fruits
0125	Growing of other fruit trees, berries, and nuts
0127	Growing of plants for beverage production
0161	Support activities for crop production
0163	Post-harvest crop activities
103	Processing and preserving of fruit and vegetables
104	Manufacture of vegetable and animal oils and fats
106	Grain processing, starch, and starch product manufacturing
1101	Distilling, rectifying, and blending of spirits
1102	Production of wine from grapes
1103	Manufacture of cider and other fruit wines
1104	Production of other non-distilled fermented beverages
1105	Brewing of beer
1106	Manufacture of malt

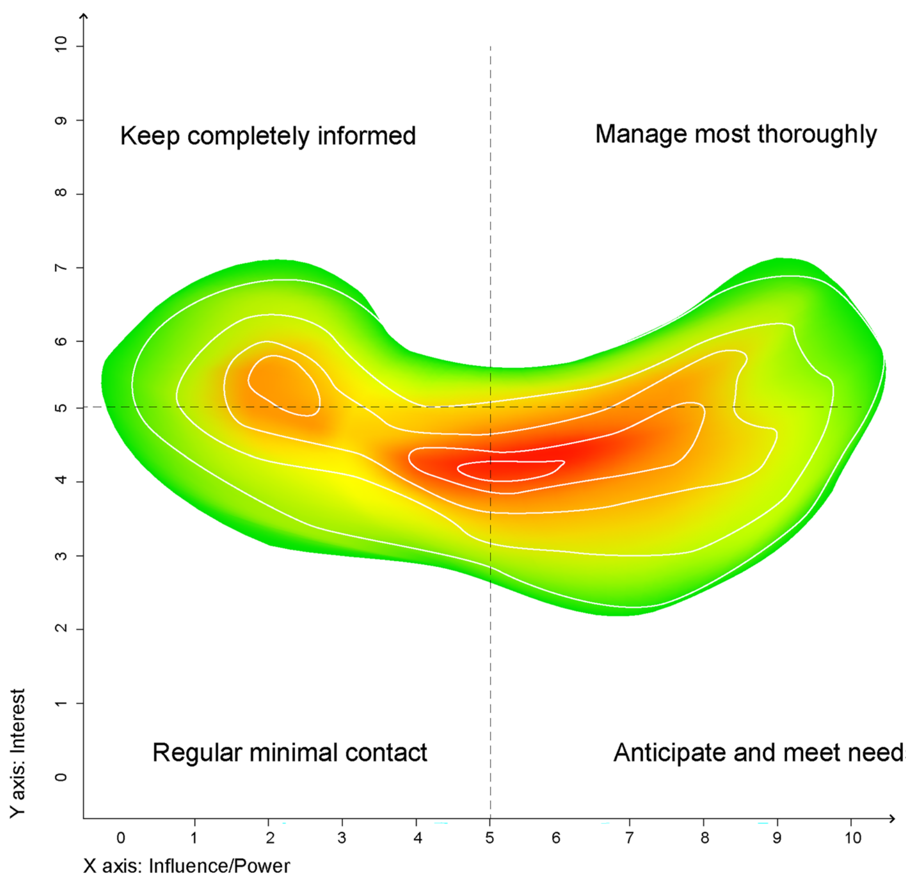

Fig. 2 Heatmap showing the distribution of stakeholders in the influence/interest matrix

Given that there is no universally established method for determining response rate estimates, the selected sample of 31 companies is considered adequate and representative for conducting the study and for developing accurate results (Johnson 2004).

Survey setup

A survey was created to gather information about the company's features and assess its interest in adopting insect biorefinery. The questionnaire was created using Google Forms to be accessible to a wide audience and minimize interpretation errors. Each participant provided informed consent, according to the European Data Protection Regulation (EU 679/2016) (European Commission 2016). To enhance comprehension and deliver accurate responses, key components such as survey length, topic relevance, cognitive burden, and frequency of survey requests as suggested by Guin et al. (2012) were considered. Before the distribution of the questionnaire, the survey was first tested on a small sample (5 companies) of participants not included in the main study sample to identify any potential problems related to the survey flow, any ambiguities, confusing questions, or response options, making the necessary adjustments based on the feedback received.

The final questionnaire consisted of four main sections. Table 3 presents details on the survey questions, items, and response options. The extended version of questionnaire is available in Table A.1, A.2, A.3, and A.4 (Additional file 1). The authors developed the questions by adapting references (Pagliacci et al. 2020; Knierim et al. 2018).

Company information

In this section, the companies were asked about their dimension (4 response options: micro, small, medium, large business), productive category (6 response options: vegetables, cereals, brewing, winemaking, distillation, and others), and their role in the food supply chain (4 response options: producer, distributor, packager, consortium). Moreover, relevant questions concerned their by-products in terms of quantity and type (free text), seasonality (yes/no), and their current management (2 response options: in-company, out-company + 6 response options: anaerobic digestion, composting, bio-stabilization, animal feed, distillation, solidarity market, other). Furthermore, the presence of a biogas plant and abandoned warehouses in the company was investigated (yes/no). Finally, the familiarity with insect farming as a method to biorefine by-products was tested (yes/no).

Interest in insect rearing

In this section, the interest of the company manager in insect rearing as an innovative way of by-product management was tested. The willingness of the by-product producers to sell their by-products to insect-rearing companies was verified (3 response options: yes, no, maybe). If the answer provided was "no," the reason for the aversion was investigated, proposing six options of response: I adhere to a vegan/vegetarian lifestyle, I do not like insects, I have no interest in changing by-products' management methods, I do not have by-products, It is not part of my image strategy, Skepticism.

Table 3 Information on the companies, willingness toward insect rearing, willingness toward the use of insect frass, and various feedback. Number of items, rating scale, and response options. References: developed by the authors

Section	Question	Items	Scale and response options	
2.2.1. Company information	Company data	2	Micro-business Small-business Medium-business Large-business	Yes/no
	Productive category and supply chain	2	Vegetables Cereals Brewing Winemaking Distillation Others	1st/2nd/3rd/4th range producer, Distributor, Packager, Consortium
	By-products and management	4	Yes/no Type and quantity	In-company Out-company Anaerobic digestion, Composting, Bio-stabilization-landfill for agronomic use, Animal feed, Distillation Solidarity market, Other
	Biogas	2	Yes/no	
	Photovoltaic	3	Yes/no	
	Abandoned warehouse	2	Yes/no	
	Innovation	2	Yes/no	
2.2.2. Interest in insect rearing	Willingness to be part of the insect-rearing supply chain	2	Yes, no, maybe	I adhere to a vegan/vegetarian lifestyle, I don't like insects, I have no interest in changing by-products's management methods, I don't have by-products, It is not part of my image strategy, Skepticism, lack of information
2.2.3. Interest in the use of insect frass	Willingness to use insect frass	2	Yes, no, maybe	Yes in 1 year, yes in 5 years, yes in 10 years, no
2.2.4. General feedback from companies	Various questions and update	2	Free text	Yes/no
	Possibility of financing	1	5-point Likert scale (1 = not at all; 5 = a lot)	

Interest in the use of insect frass

This section tested the company manager's interest in using insect frass as a natural soil enricher. First, the company was asked if, as an agricultural producer, it would be interested in using frass for its farm (three response options: yes, no, maybe). Then, the willingness to be part of an IB supply chain was investigated (four response options: yes in 1 year, yes in 5 years, yes in 10 years, no).

General feedback from companies

In this section, general feedback from the companies under investigation was collected. Offering the possibility to respond via free text, they were asked what questions they would like to ask about the proposal to start an insect farm. The influence of regional tenders on starting a Circular Economy supply with insect rearing was investigated using a 5-point Likert scale (1: totally disagree; 5: totally agree). Finally, the company was asked if it was interested in receiving updates regarding insect farming (yes/ no).

Data elaboration and statistical analysis

The data collected from each question were organized and expressed as the number of companies that provided a specific response, first as a percentage of the total sample and then as a percentage of the respective group to which they belonged (L-P or T region, respectively). Moreover, for the section "2.2.1. Company information", the median, mean, interquartile range, and standard deviation were calculated. The survey questions were selected for conducting principal component analysis (PCA), resulting in 27 qualitative responses per company to be included in the data analysis (Table 4). Additionally, the possible answers were converted into numerical values.

The R software was used for data evaluation and interpretation (version R 4.1.2 2023) with the interface R-studio (version 2023.03.1 + 446, 2023). The packages "corr," "ggcorrplot," "ggplot2," "FactoMineR" "readxl" were utilized.

After data normalization, a correlation plot was generated, applying Pearson's correlation (Sedgwick 2012).

The correlation values can range from − 1 to + 1, where 1 represents a perfect positive correlation (the variables increase together), and − 1 represents a perfect negative correlation (as one variable increases, the other decreases). A value of 0 indicates no linear relationship between the variables. Subsequently, a PCA was applied (Kolenikov and Angeles 2009). PCA is a multivariate technique used to analyze observations described by several inter-correlated quantitative dependent variables, as was the case in this study. The term "cos2" is used to estimate the quality of representation: a high cos2 value indicates that a variable is well-represented by the principal component, while a low cos2 value indicates that the variable is not accurately represented (Priyadharshini et al. 2021).

The results were visually represented through a biplot, illustrating the variables and their relationships. The biplot aims to extract the important information from the data to represent it as a set of new orthogonal variables (called principal components) and to display the pattern of similarity of the observations and of the variables as points in maps (Abdi and Williams 2010). Variables were depicted as vectors, with the angle and length of the vectors clarifying the relationships among variables, facilitating interpretation. The evaluation of the components, conducted using cos2 analysis, enabled us to identify the relationships between attributes and their significance in explaining a specific phenomenon.

Results

Survey results

Companies information

The analysis revealed a homogeneous distribution of the total number of companies between the two areas studied (regions L-P and T, Table 5). The dimension followed the same trend in both L-P and T, with the majority of companies being micro-business

Table 4 Survey questions' selected for principal component analysis: questions, options and numerical values assigned

Variables for PCA analysis			Possible answers and numerical values assigned	
Code	Section	Question		
Q1	2.2.1–2	Dimension of the company	Micro-business, Small-business, Medium-business, Large-business	1, 2, 3, 4
Q2	2.2.1–3	Is there a research and development manager in the company?	Yes, No	1, 0
Q3	2.2.1–4.1	Productive category	Vegetable, Winemaking, Brewing, Cereals, Others	1, 2, 3, 4, 0
Q4	2.2.1–4.2	Role in the supply chain	1st range, 2nd range, 3rd range, 4th, other	1, 2, 3, 4, 0
Q5	2.2.1–5	Presence of seasonal production	Yes, No	1, 0
Q6	2.2.1–5	Specify the period of the production	Summer, Winter, Mixed seasonality	1, 0, 2
Q7	2.2.1–6	Typology of by-products	Vegetable, Winemaking, Brewing, Cereals, Others	1, 2, 3, 4, 0
Q8	2.2.1–6	Quantity of by-products	Free answer	
Q9	2.2.1–7	In-company management of by-products	Yes, No	1, 0
Q10	2.2.1–7	Off-company management of by-products	Yes, No	1, 0
Q11	2.2.1–8	Does the company have a biogas plant?	Yes, No	1, 0
Q12	2.2.1–9	Would you be willing to set up a biogas plant?	Yes, No	1, 0
Q13	2.2.1–10	Does the company have a photovoltaic system?	Yes, No	1, 0
Q14	2.2.1–11	Is the land underneath now used for any type of production?	Yes, No	1, 0
Q15	2.2.1–12	If yes, (…) are there issues?	Yes, No	1, 0
Q16	2.2.1–13	Are there unused and/or abandoned warehouses or rooms on the farm?	Yes, No	1,0
Q17	2.2.1–14	If yes, would you be willing to find a new purpose for such environments?	Yes, No	1,0
Q18	2.2.1–15	New purpose- Self-management of by-products	1 (Not at all); 2 (very little); 3 (little); 4 (enough); 5 (a lot)	1, 2, 3, 4, 5
Q19	2.2.1–15	New purpose- Self-production of energy	1 (Not at all); 2 (very little); 3 (little); 4 (enough); 5 (a lot)	1, 2, 3, 4, 5
Q20	2.2.1–15	New purpose- Receive funding to activate circular economy practices	1 (Not at all); 2 (very little); 3 (little); 4 (enough); 5 (a lot)	1, 2, 3, 4, 5
Q21	2.2.1- 15	New purpose- Start a new production	1 (Not at all); 2 (very little); 3 (little); 4 (enough); 5 (a lot)	1, 2, 3, 4, 5
Q22	2.2.1–16	Are you familiar with insect farming as a method to biorefine by-products?	Yes, No	1, 0
Q23	2.2.2–1	Would you be willing to sell your by-products to insect biorefinery companies?	Yes, No, I do not know	1, 0, 0.5
Q24	2.2.3–1	If you're a producer, would you like to use frass as a soil improver for your crops?	Yes, No, I do not know	1, 0, 0.5
Q25	2.2.3–2	Would you be willing to be part of an insect farming supply chain?	No, yes in 1 year, yes in 5 year, yes in 10 years	0, 1, 2, 3
Q26	2.2.4–1	On a scale from 1 to 5, how much the possibility of participating in regional tenders to obtain financing for starting a Circular Economy supply chain would influence your propensity to insect-rearing activity?	1 (Not at all); 2 (very little); 3 (little); 4 (enough); 5 (a lot)	1, 2, 3, 4, 5

Table 4 (continued)

Variables for PCA analysis			Possible answers and numerical values assigned	
Q27	2.2.4–2	Would you be open to receiving news or updates regarding regional insect farming opportunities?	Yes, No	1,0

Table 5 Data collected by section "2.2.1. Company information" of the survey concerning company information. Data are expressed as the number of companies and percentage on the total, in the group "L-P" and in the group "T"

2.2.1. Company information	Information	Total	% on Total	L-P	% on L-P	T	% on T
Number of companies		31	100	17	100	14	100
Dimension	Micro-business	22	70.9	13	76.5	9	64.3
	Small-business	8	25.8	4	23.5	4	28.6
	Medium-business	1	3.23	0	0.00	1	7.14
	Large-business	0	0.00	0	0.00	0	0.00
R&D in the company	Yes	11	35.5	7	41.2	4	28.6
	No	20	64.5	10	58.8	10	71.4
Productive category	First-range producer	31	100	19	112	12	85.7
	Second range producer	3	9.68	3	17.6	0	0.00
	Third range producer	3	9.68	3	17.6	0	0.00
	Four range producer	2	6.45	2	11.7	0	0.00
	Distributor	3	9.68	2	11.7	1	7.14
	Packager	6	19.3	3	17.6	4	28.6
Role in the supply chain	Brewing	4	12.9	4	23.5	0	0.00
	Distillation	1	3.23	1	5.88	0	0.00
	Winemaking	15	48.4	8	47.1	7	50.0
	Cereal producers	5	16.1	3	17.6	2	14.3
	Animal husbandry	2	6.45	2	11.7	0	0.00
	Beekeeping	1	3.23	1	5.88	0	0.00
	Vegetable producers	10	32.3	4	23.5	6	42.9
	Oil producers	1	3.23	0.00	0.00	1	7.14

T Trento and Bolzano (Trentino-Alto Adige Region); *L-P* (Lombardy, Piedmont and Emilia Romagna Regions)

(76% and 64%, respectively), followed by small and medium-sized businesses. The sample did not include large companies. Interestingly, the R&D department was present in about half of the L-P companies (41%), while in the Trentino region, it was present in only 28 of the companies. L-P companies were mainly first-range producers; moreover, many companies had more than one type of production where they appeared as first-range producers. A minority of L-P companies were employed at another point of the supply chain (around 11–17% for each category). The T companies were mainly first-range producers (85%), with the remaining operating as distributors or packers. The most widespread production categories in L-P were winemaking (47%), brewing (23%), and vegetable production (23% of the companies). On the contrary, the production in the Trentino region was concentrated in viticulture (50% of the companies), followed by vegetable producers (42%) and a minority of cereal producers (14%).

By-products type and management

Regarding the area's productive vocation (Table 6), the by-products of L-P companies were mainly represented by fruit and vegetable by-products, pomace, lees, and threshers (17% for each type), while T companies produced fruit and vegetable by-products and pomace (21% for each type), followed by grape stems (14%).

In terms of quantity, the winemaking by-products represented the majority of waste (65%) from L-P companies, with the remaining portion consisting of oil pomace. Similarly, in T, most of the waste was from winemaking, while the other half consisted of oil pomace. According to this data, the majority of producers declared having seasonal production, mostly occurring during the summer period. A majority (57%) of T

Table 6 Data collected by Section "2.2.1. Company information" of the survey concerning by-product type, quantity, and management. Data are expressed as the number of companies and percentage on the total, in the group "L-P," and in the group "T"

2.2.1. Company information	Information	Total	% on Total	L-P	% on L-P	T	% on T
By-products type	Fruit and vegetable	6	19.4	3	17.6	3	21.4
	Pomace	6	19.4	3	17.6	3	21.4
	Stem from grape	3	9.7	1	5.88	2	14.3
	Lees	4	12.9	3	17.6	1	7.14
	Threshers	3	9.68	3	17.6	0	0.00
	Cereal by-products	2	6.45	2	11.7	0	0.00
	Oil pomace	1.00	3.23	0	0.00	1	7.14
By-products quantity (tons)	Fruit and vegetable	128	15.6	12.6	15.3	116	15.6
	Pomace	159	19.2	31.0	37.8	12	17.2
	Stem from grape	105	12.7	15.0	18.3	90.0	12.1
	Lees	20.4	2.47	19.4	23.6	1.00	0.13
	Threshers	4.00	0.48	4.00	4.87	0.00	0.00
	Cereal by-products	0.10	0.01	0.10	0.12	0.00	0.00
	Oil pomace	409	49.5	0.00	0.00	409	54.9
Seasonal production	Yes	23	74.2	12	70.6	11	78.6
	No	12	38.7	9	52.9	3	21.4
	Mixed	3	9.68	2	11.7	1	7.14
Type of seasonality	Summer	18	58.1	8	47.1	10	71.4
	Summer–winter	4	12.9	3	17.6	1	7.14
In-company management	Number	13	41.9	5	29.4	8	57.1
Methods	Bio-stabilization-landfill for agronomic use	2	6.45	2	11.7	0	0.00
	Animal feed	4	12.9	2	11.7	2	14.3
	Composting	8	25.8	1	5.88	7	50.0
	Distillation	2	6.45	0	0.00	2	14.3
	Other	1	3.23	1	5.88	0	0.00
Out company management	Number	19	61.3	12	70.6	7	50.0
Methods	Bio-stabilization-landfill for agronomic use	3	9.68	2	11.7	1	7.14
	Animal feed	5	16.1	3	17.6	2	14.3
	Composting	11	35.5	6	35.3	5	35.7
	Distillation	2	6.45	1	5.88	1	7.14
	Other	2	6.45	2	11.7	0	0.00

T Trento and Bolzano (Trentino-Alto Adige Region); *L-P* (Lombardy, Piedmont and Emilia Romagna Regions)

companies managed their by-products internally (in-company), utilizing composting techniques (50% of companies), using them for animal feed (14%) or for the distillation process (14%). On the contrary, half of T companies opted for external (out-company) management, using composting, agronomic utilization, and animal feed. These data suggested that T companies also employed a combination of internal and external management methods. In the L-P scenario, 70% of the companies managed their by-products externally through methods such as composting (35% of companies), animal feed (17%), and agronomic utilization (11%). A smaller portion of L-P companies (29%) utilized internal management, choosing among animal feed, agronomic use, composting or other.

Regarding L-P companies, none of them overlap with other management systems.

Additional information on the companies

Considering both L-P and T companies, most, if not, all of them did not have a biogas plant, nor were they interested in its implementation (Tables 7 and 8). The same trend was observed regarding the presence of photovoltaic systems. In the few cases where companies were equipped with this system, they declared that the soil underneath was not used for agricultural production.

Once again, most of the companies did not have abandoned warehouses or rooms.

As expected, companies were not familiar with insect rearing in both the L-P and T regions (76% of L-P companies and 85% of T companies, respectively).

Table 7 Data collected by section "2.2.1. Company information" of the survey concerning the innovation level of the company and the tendency to implement green methods in the company. Data are expressed as the number of companies and percentage on the total, in the group "L-P," and in the group "T"

2.2.1. Company information	Information	Total	% on Total	L-P	% on L-P	T	% on T
Does the company have a biogas plant?	Yes	1	3.23	1	5.88	0	0.00
	No	30	96.7	16	94.1	14	100
Would you be willing to set up a biogas plant?	Yes	0	0.00	0	0.00	0	0.00
	No	29	93.5	15	88.2	14	100
	Yes but I don't know when	2	6.45	2	11.7	0	0.00
Does the company have a photovoltaic system?	Yes	18	58.1	12	70.6	6	42.9
	No	13	41.9	5	29.4	8	57.1
If you have a photovoltaic greenhouse, is the land underneath now used for any kind of production?	Yes	2	6.45	0	0.00	6	42.8
	No	12	38.7	7	41.2	8	57.1
Are there unused and/or abandoned warehouses or rooms in the farm?	Yes	4	12.9	2	11.7	2	14.3
	No	27	87.1	15	88.2	12	85.7
If yes, would you be willing to find a new purpose for such environments?	Yes	6	19.3	3	17.6	3	21.4
	No	0	0.00	0	0.00	0	0.00
Are you familiar with insect farming as a method to biorefine by-products?	Yes	6	19.3	4	23.5	2	14.3
	No	25	80.6	13	76.5	12	85.7

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Table 8 Data collected by section "2.2.1. Company information," question 15. Degree of interest of the companies toward new purposes for their by-products management on a scale from 1 to 5

2.2.1. Company information	**Total**				**L-P**				**T**			
Reasons of interest in self- management of by-products:	M	Iqr	m	SD	M	Iqr	m	SD	M	Iqr	m	SD
Self-production of energy	2.50	1.50	2.50	1.20	3.50	1.25	3.25	0.96	2.00	1.00	2.00	1.00
Receiving funding for innovative activities	4.00	1.00	4.38	0.52	4.00	0.25	4.25	0.50	4.50	1.00	4.50	0.58
Start a new production	3.50	1.75	3.17	1.47	3.50	1.50	3.50	1.29	2.50	1.50	2.50	2.12

T Trento and Bolzano (Trentino-Alto Adige Region); *L-P* (Lombardy, Piedmont and Emilia Romagna Regions); *M* Median, *m* mean, *Iqr* Interquartile range; *SD* standard deviation

Interest in insect rearing

As shown in Table 9, the willingness of companies to participate in the insect-rearing system was investigated. Among L-P companies, only 17% were interested in selling their by-products for insect-rearing purposes, while the majority indicated no interest (58%). In the Trentino region, almost all companies either chose “not interested” (42%) or “maybe interested” (50%), with only 7% of them expressing interest. The motivation behind this behavior varied by geographic region. In L-P companies, disinterest in insect rearing was mainly driven by a willingness not to change the current management method (23%), skepticism, and lack of information (17%), and only 11% of companies viewed insects as not part of their image strategy.

In T companies, the main reasons included “not changing current management method” (28%) and not viewing insects as part of their image strategy (14% of companies). The tendency to use frass as a soil improver was limited, with 35% of companies in L-P and 21% in the T region expressing no interest.

Regarding interest in becoming part of an insect farming supply chain, most responses from L-P companies indicated “not interested,” while around 16% of companies may consider it in 1–5 years. Similarly, T companies were not interested in this activity (78%), with some considering insect rearing within the next 1–5 years (21%), while none were interested at the time of the survey. In terms of the insect sector, companies expressed a need for more general information, as suggested by data from the L-P area, as well as detailed information on the production process. Only one company from each geographical group indicated a need for information on the final use of insects. As a final question, interest in receiving information about regional insect farming opportunities was investigated. Equal numbers of L-P companies responded positively and negatively, whereas 32% of companies in the T region showed no interest.

Survey elaboration

Based on the survey, relevant points were broken down into 27 variables, aiming to understand and highlight the most relevant factors influencing farmers’ acceptance toward innovative management techniques, particularly insect rearing.

The correlation plot, presented in Fig. 3, illustrates the relationship among these variables which are detailed in Table 4.

The variables Q16–Q21 showed a strong positive correlation among them. This refers to the questions concerning the presence of abandoned warehouse (Q16), willingness to find new purposes for them (Q17), interest in self-management of by-products (Q18), in self-production of energy (Q19), in receiving funding for implementing circular economy practices (Q20), and interest for starting a new production (Q21).

On the other hand, Q13 (the presence of photovoltaic systems in the company) stood out as the most relevant negative correlation. Q13 was negatively correlated with nearly half of the variables, particularly Q9 (in-company by-products management), Q15 (issues related to cultivation under photovoltaic plant) and Q26 (interest in taking part in regional tenders).

Additionally, numerous lacks of correlations were detected, such as Q2–Q6 (questions concerning the company production type and presence of internal R&D, role in the supply chain, by-products production). It is important to note that while some variables are correlated, this does not imply a direct causal relationship.

The results of the PCA analysis of the 27 variables are presented in Fig. 4. The analysis was performed across Dimension 1 and Dimension 2, which explained 47.2% and 12.2% of the data variance, respectively.

In the upper right quadrant, variables such as company size (Q1), role in the supply chain (Q4), quantity of by-products (Q8), and greenhouse utilization and related issues (Q14, Q15) were positively correlated. Notably, Q1 had the highest cos2 index, indicating its strong contribution to this quadrant. The lower right quadrant included variables such as the presence of internal R&D (Q2), seasonal production patterns (Q6), management of by-products outside the company (Q10), greenhouse presence (Q13) and willingness to manage by-products through insect rearing (Q23). These variables were

Table 9 Sections "2.2.2. Interest in insect rearing" and "2.2.3. Interest in the use of insect frass" of the survey collected data regarding general interest in the insect-rearing sector. Data are expressed as the number of companies and percentage on the total, in the group "L-P," and in the group "T"

2.2.2. Interest in insect rearing **2.2.3. Interest in the use of insect frass**	**Information**	**Total**	**% on Total**	**L-P**	**% on L-P**	**T**	**% on T**
Would you be willing to sell your by-products to insect biorefinery companies?	Yes	4	12.9	3	17.6	1	7.14
	No	16	51.6	10	58.8	6	42.9
	Maybe	11	35.5	4	23.5	7	50.0
If not, why?	No interest in changing by-products' management methods	8	25.8	4	23.5	4	28.6
	No by-products	2	6.45	2	11.7	0	0.00
	Not part of my image strategy	4	12.9	2	11.7	2	14.3
	Skepticism, lack of information	3	9.68	3	17.6	0	0.00
If you're a producer, would you be interested in using frass as a soil improver for your crops?	Yes	3	9.68	1	5.88	2	14.3
	No	9	29.0	6	35.3	3	21.4
	Maybe	4	12.9	1	5.88	3	21.4
Would you be willing to be part of an insect farming supply chain?	Yes	0	0.00	0	0.00	0	0.00
	Yes, in 1 year	3	9.68	1	5.88	2	14.3
	Yes, in 5 years	3	9.68	2	11.8	1	7.14
	No	24	77.4	13	76.5	11	78.6
What questions would you ask someone who offers you to start the activity of insect-rearing?	General information (costs, necessary resources, timing)	9	29.0	6	19.3	3	9.68
	Information on the production activity (management of insect breeding, operations and necessary materials)	6	19.3	2	6.45	4	12.9
	Information on the final use of insects (use as feed, food, other)	2	6.45	1	3.23	1	3.23
Would you be open to receive news or updates regarding regional insect farming opportunities?	Yes	12	38.7	8	25.8	4	12.9
	No	19	61.3	9	29.0	10	32.3

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strongly explained by Dimension1, with Q10 providing the greatest contribution. Additionally, a strong correlation was observed between Q6 and Q10. In the lower left quadrant, variables were positively correlated included production category (Q3), presence of seasonal production (Q5), type of by-products (Q7), presence of abandoned warehouse (Q16), knowledge on insects' rearing (Q22), willingness to enter the insects' supply chain (Q25), interest in taking part in regional tenders (Q26) and interest in receiving news on insect-rearing advancement (Q27). These were negatively correlated with the variables in the upper right quadrant.

Finally, in the upper left quadrant, the variables with the highest cos2 index were found. These included interest in self-production of energy (Q19), interest in receiving funding (Q20), interest in innovative production (Q21), interest in finding new purposes for abandoned warehouse (Q17), and self-management of by-products (Q18), all of which contributed significantly to Dimension 2. Additionally, variables related to in-company management (Q9), the presence of biogas plant e/o willingness in implementing a biogas plant (Q11), and willingness to use frass for their own cultivation (Q24) pointed in the same direction. Strong positive correlations were observed between Q18 and Q21, Q11 and Q24, and Q19 and Q20.

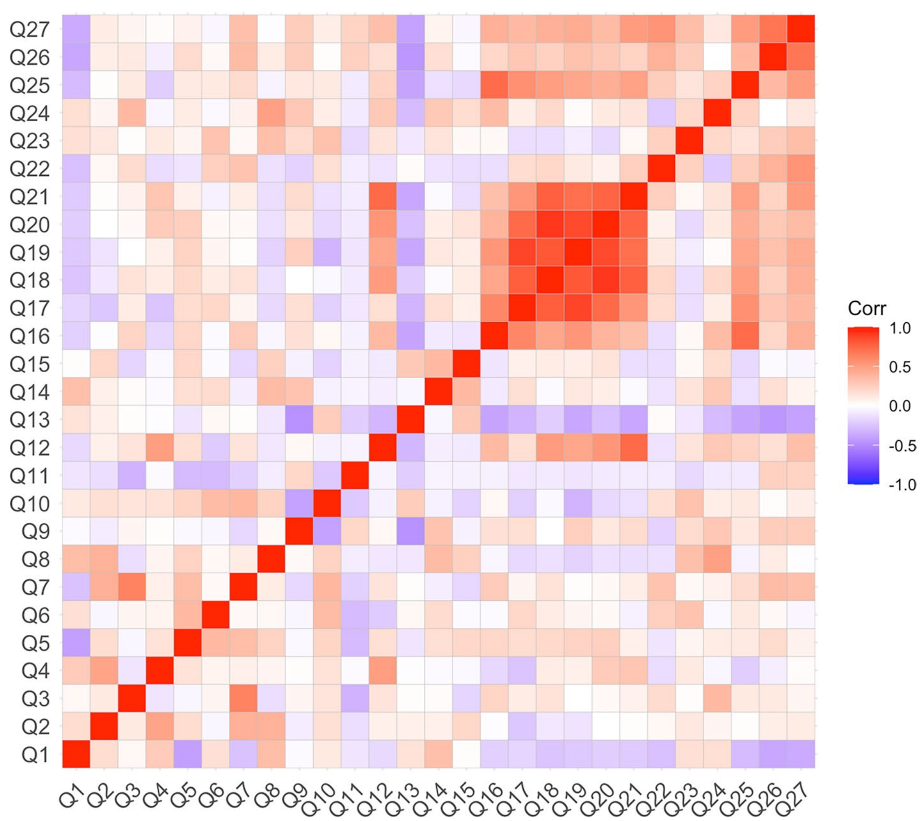

Fig. 3 Correlation plot of the variables (Q1–Q27)

Discussions

The development of new technologies for alternative proteins is becoming crucial for transitioning to more sustainable food systems (Prause et al. 2021). Among these innovations, the use of insects in human and animal production has gained significant attention from policymakers and is now a pivotal component of the food policy agenda (Mylan et al. 2023). This growing interest highlights the need to understand the factors that influence the adoption of insect biorefinery (IB) by upstream symbiosis partners (USPs), as this adoption plays a vital role in achieving sustainability goals. The current study aims to explore these factors and their implications for USPs' adoption of IB.

The majority of the companies analyzed consisted of micro-businesses in the first-range category, lacking R&D capabilities. Fruits and vegetables represent the main by-products available in the area, which are primarily managed by out-company methods. In fact, in-company management was utilized by only 41% of the companies, while off-company management accounted for 61%. Most companies did not have a biogas plant (96%) but 58% of them did have a photovoltaic system.

Unfortunately, a high percentage of companies (80%) declared to be not familiar with insect farming as a method for biorefining by-products. Considering the interest in setting-up innovative production methods, "receiving funding for innovative activities" was the main driver for this attitude. Skepticism toward insect farming was evident in the survey responses related to the insect rearing and the use of frass. In fact, the companies showed no interest in either becoming directly involved in the insect production-chain or selling their by-products to insect producers. However, respondents expressed

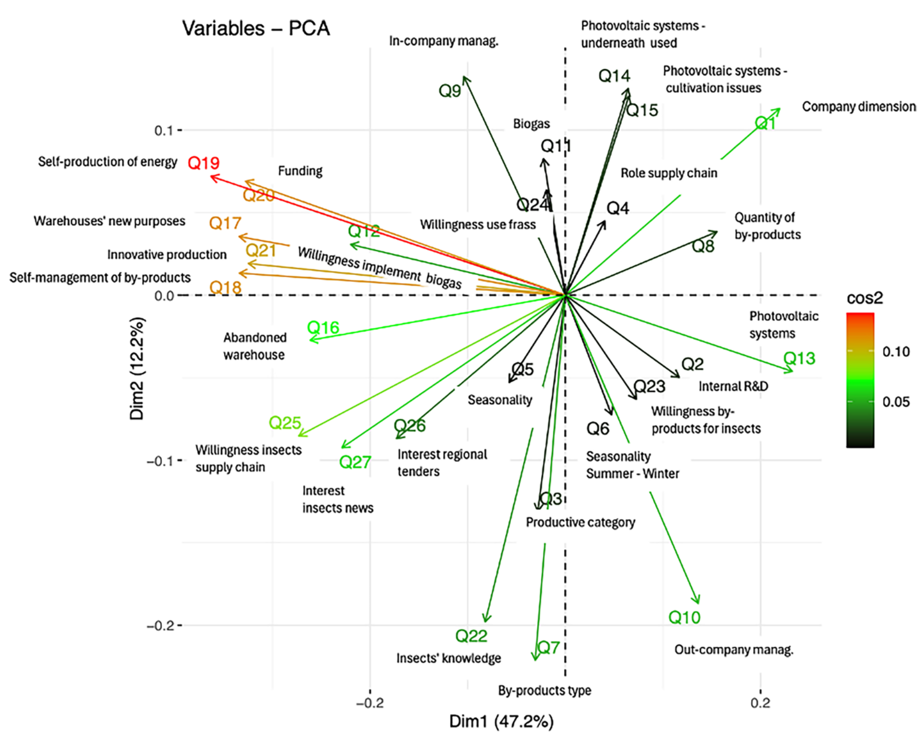

Fig. 4 Contribution of variables to the principal components (Dim 1 and Dim 2), along with the cos2 scores

curiosity about insect farming, indicating a willingness to seek general information regarding costs and the resources needed to implement this activity.

The correlation plot revealed a strong relationship between the presence of abandoned warehouse and the interest in finding new activities and innovative methods for by-product management, underling the interest of companies to improve and enhance the efficiency of their activities.

Interestingly, interest in receiving updates on the insect sector was negatively correlated with company size and presence of internal R&D. This indicates that micro and small businesses have a more positive attitude toward insect-based innovations compared to larger companies. It is likely that large companies require more time and detailed information to implement new strategies into their long-term vision, whereas small companies' owner are more inclined to experiment with innovations to grow their business and differentiate themselves from competitors.

The PCA analysis provided valuable insights into the data collected from the companies. In particular, the seasonality of by-products was strongly associated with out-company management, highlighting a preference in adopting external systems handling to simplify operations. A common interest in innovation and sustainability drove interest in both receiving regional funding and self-producing energy. Additionally, a strong correlation was observed between the variables representing interest in innovative production methods and self-management of by-products.

Variable Q19, which represents interest in self-production of energy, was the primary driver of Dim2, with the highest cos2 score. In contrast, variables such as willingness to use frass, role in the supply chain, seasonality, and production category had a low cos2 score, indicating a lower contribution to explaining the variance in the data.

Company size was negatively correlated with knowledge of the insect-rearing process and interest in receiving news on this topic. It is evident that as company size increases, the predisposition to join the insect supply chain decreases. Additionally, the type of by-products available was closely related to the willingness to adopt insect biorefinery, highlighting challenges in managing certain materials e/o procedures already consolidated for others.

As expected, indicators of innovation predisposition (represented by interest in innovative production, self-management of production, self-production of energy, and willingness to implement a biogas plant) were negatively influenced by the attitude of out-company management. Surprisingly, the predisposition toward innovation among farmers was negatively correlated with the presence of internal R&D within the company.

Insect farming and biorefinery are generally characterized by negative attitudes and beliefs by consumers in Western countries, including Italy (Sogari et al. 2023). Previous studies (Verbeke et al. 2015; Weinreis et al. 2023) have demonstrated that the opinions of different stakeholders on the use of insects vary depending on their use as livestock feed or human food. However, no study has investigated the attitude of potential USPs toward IB across both developed and developing countries.

Our results are relevant to policymakers and associations interested in IB for by-product upcycling, as they highlight the impact of different key factors influencing USPs' willingness to participate in the IB supply chain. The findings provide insight into specific IB cases in Northern Italy. It is the first study on this subject aiming at developing collaborative IB value chains across Europe toward circular economy implementation.

Specifically, IB can be promoted in Europe in general, in Italy and in the research area, through a multi-pronged strategy, for instance:

1. As revealed by the PCA analysis, the possibility of receiving funding for innovative activities plays a key role for company owners in establishing new types of production. In this sense, public and private investment in IB promotion should be encouraged. Because IB is still an unfamiliar niche for most farmers (Tavares et al. 2022), establishing demonstration plants and Q&A events to answer farmers' doubts can spread awareness among farmers and influence their propensity to adopt the technology, as our results underlined. In the context of agricultural innovation, the visibility and accessibility of demonstration plants have been identified as key factors influencing farmers' adoption decisions (Nejadrezaei et al. 2018; Vecchio et al. 2020).
2. Local community awareness should be also increased to promote IB among farmers. Consumer acceptance of products derived from IB or circular economy activities remains a barrier or leverage for circular economy technology adoption (Ardoin and Prinyawiwatkul 2021). This is consistent with the "Technology Readiness Index" (TRI) paradigm, which argues that discomfort and insecurity toward a technology act as inhibitors of acceptance and have a negative relationship with technology adoption (Lima et al. 2018). Similarly, the doubts surrounding companies' image strategy, skepticism toward IB and reluctance to change by-products management methods, that arose from our survey, align with the concept of "loss aversion" (Kahneman and Tversky 1979), which considers losses (in this case, leakage of consumer acceptance or loss of advantageous handling practices) twice as powerful as equivalent gains in adopting an innovation. Although the data analysis revealed a limited interest in receiving news about insect rearing, the companies raised intriguing questions while completing the survey highlighting their need to learn more about this innovative production method. Emphasizing the benefits for livestock and environmental perks of insect-based products may help increase market acceptance of IB and insect-based products by reasoning with consumers who priorities sustainability and livestock welfare (Sogari et al. 2023; Verbeke 2015). Consequently, increasing market acceptance could boost purchases, thus lowering companies' risk aversion.
3. Achieving the benefits of IB technology, including nutrient upcycling, requires favorable government policies and recognition of the technology as an optimal strategy from an ESG (Environmental, Social, and Governance) perspective, enhancing its attractiveness to investors, consumers, and other stakeholders. Moreover, the opportunity for companies to exploit unused resources is a significant driver behind their decision to implement insect rearing, as revealed by the PCA analysis. This has already been experienced for biogas across EU member states (Horschig et al. 2020; Scarlat et al. 2018) and worldwide in general (Jan and Akram 2018; Wang et al. 2020). Although the factors examined in this study are crucial in adoption studies of sustainable agriculture practices (Pagliacci et al. 2020), it is important to note that adoption behavior is sensitive to variations of factors such as (1) farm and farmer-specific characteristics, (2) social and cultural norms, (3) availability of support and

resources, and (4) perceived financial benefit (Yang and Wang 2023). To further investigate factor (1), future research could involve Norm Activation Model (NAM) predicting the intention of an individual through the influence of personal norms toward IB (Savari et al. 2023). Additionally, quantitative assessments require more cases to draw meaningful conclusions. Although the number of respondents in this study was sufficient for conducting a PCA analysis, it may lack representation, which is one of the limitations. This should be considered when interpreting the results to ensure a more accurate and balanced understanding of the data.

Therefore, further studies should ensure that the sample of respondents is more representative and includes a more comprehensive range of adoption factors.

Conclusions

USPs attitudes toward IB adoption were evaluated through an online questionnaire. Small farm size and attitude toward on-farm by-product management were identified as drivers for the acceptance of this technology to upcycle nutrients.

At the same time, characteristics such as negative consumer perception and personal neophobia were recognized as barriers to the open-ended questions, consistent with the TRI paradigm and “loss aversion” concept. This study provides insights into potential UPS profiles for upscaling this technology niche. Our study contributes to this ongoing dialogue by shedding light on the interplay between knowledge level, company dimension, and sustainability attitudes among northern Italian farmers, illuminating avenues for future research and practical implementation in the European IB sector. Our findings highlight the significance of favorable government policies and recognition of technology, public and private investment in IB promotion, and the promotion of local community awareness. Establishing demonstration plants, enhancing IB’s attractiveness to investors, consumers, and other stakeholders and emphasizing the benefits for livestock and the environmental benefits of insect-based products among consumers may help increase UPSs’ acceptance of IB.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40100-024-00336-4.

Additional file 1.

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Author contributions

C.P. and A.C. contributed to conceptualization; data curation; and writing—original draft; S.D. and M.M. were involved in methodology and writing—review and editing; C.M. contributed to writing—original draft, and data curation; and S.B. and S.D. were involved in writing—review and editing, and supervision.

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Availability of data and materials

The datasets used and analyzed during the current study are not available since confidential information.

Declarations

Competing interests
The authors declare that they have no competing interests.

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