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Research Paper

Local circular economy: BSF insect rearing in the Italian Agri-Food Industry

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ABSTRACT

With a growing population, both food and waste production will increase. There is an urgent need for innovative ways of valorizing waste. The black soldier fly (*Hermetia illucens* L.) efficiently converts agri-food by-products (BPs) into high-quality materials; its rearing process yields larvae (BSFL) rich in fat and protein for feed purposes, with "frass" acting as organic fertilizer. While the insect rearing sector is expanding, few producers use BPs. Therefore, a case study approach was adopted to evaluate the potential for establishing an Italian BSFL production plant on BPs available on the territory. After contacting more than 115 agri-food companies (maximum 100 km from the BSFL plant), they were classified based on sector, distance, size, and BPs (quantity, seasonality, management). BPs with a low value (fruit and vegetable residues) were treated as waste, associated with costs and low valorization. By merging the available BPs on the territory and following the literature on BSFL nutritional needs' two diets (Scenario BSFL) were created, assessing their suitability comparing them to the current full-scale plant diet (Scenario 0). The exploitation of BPs for BSFL rearing reduced local waste production by 52 % compared to conventional composting (Scenario 0). In addition, integrating BPs into the larval feed formulation increased BSFL production value (+47 times). These results highlight the potential of locally-based insect rearing to valorize BPs and create a network of sustainable actors within the agri-food industry. Further investigations are needed to improve the connection between agri-food and insect industrial activities, expanding this framework to other regions.

1. 1 Introduction

The FAO has estimated that approximately one-third of the world's food is lost or wasted every year, accounting for 30 % of total production. The percentage of food loss primarily involves roots, tubers, and oil-bearing crops (25.3 % of total food loss), fruits and vegetables (21.6 %), meat and animal products (11.9 %), other categories (10.1 %), and eventually cereals and pulses (8.6 % of total food loss) (FAO, 2019). More precisely, the term "food loss" refers to the decrease in weight or nutritional value of food that was originally intended for human consumption. Food waste is generated during the different steps of production (primary production, industry transformation, and distribution) and contributes to the fraction wasted by the final consumers. The EU waste hierarchy in the food industry is based on three principles: (i) waste prevention, (ii) reuse, recycling, and recovery, and iii) disposal without pre-treatment is forbidden (EC, 2008). The agri-food residues are currently managed as waste and are subject to degradative processes such as composting, sometimes incurring economic cost for the producers and yielding limited economic value of the final products (Barbi et al., 2020; Gligorescu et al., 2020). The transition of the agri-food sector to a circular economy aims to achieve the most efficient use of agricultural waste by reusing and recycling it, creating agricultural closed loops (Donner & de Vries, 2021; Voukkali et al., 2023).

More in detail, the concept of a circular economy "is a systems solution framework that tackles global challenges such as climate change, biodiversity loss, waste, and pollution. It is based on three principles, driven by design: eliminate waste and pollution, circulate products and materials at their highest value, and regenerate nature (Ellen MacArthurFoundation, 2021).

Applying this vision, biomasses could be efficiently employed as feedstock for promising alternative approaches, such as the rearing of saprophytic organisms, particularly the Black Soldier Fly (BSF; *Hermetia illucens* L.; Craig Sheppard et al., 1994; Diener et al., 2011; Oonincx & Boer, 2012). The BSF is a non-pest insect characterized by high voracity (Čičková et al., 2015), being able to grow on agri-food biomasses, reducing food waste, and creating at the same time new feed ingredients.

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Since BSF is non-pathogenic, not a vector of disease (Čičková et al., 2015), and requires precise ranges of temperature and humidity to live, in case of escape, no negative effects on the environment or the ecosystem or uncontrolled growth are expected. Its life cycle is composed of five stages: egg, larvae, pre-pupa, pupa, and adult (Grunert et al., 2015). The major commercial relevance is for the larval stage (BSFL), which is achieved in 6–7 days in a full-scale plant (Raksasat et al., 2020). Considering the feed sector, mainly pigs, poultry, and aquaculture, BSFL is considered a valid protein alternative to soybean meal and fishmeal (Gligorescu et al., 2020; European Commission, 2009, 2011, 2017, 2021). BSFL has a high gross energy content and does not accumulate aflatoxins (Barragan-Fonseca et al., 2017; Gulsunoglu et al., 2019; Meijer et al., 2019; Purschke et al., 2017; Wang & Shelomi, 2017). Moreover, insect fat has been studied as a replacement for fish oil in aquaculture and animal feed, recording improvements in the health status of the animals (Biasato et al., 2019; Fawole et al., 2021; Kar et al., 2021; Makkar et al., 2014; Spranghers et al., 2018; Star et al., 2020). At the end of the rearing process, beside the production of larvae for feed purposes, the residual of the rearing substrate is called "frass" and is rich in nitrogen, phosphorus, and potassium. It is a profitable alternative to other organic fertilizers (Beesigamukama et al., 2020; Klammsteiner et al., 2020; Osimani et al., 2018). Considering the regulatory framework in industrial insect-rearing systems, the EU prohibits the use of animal-origin products (except milk, eggs, and derived products) and municipal waste, especially organic fractions of municipal solid waste (European Commission, 2001, 2009). On the contrary, the use of residues from the vegetal food industry as dietary substrate for insects is allowed (Regulation EC 767/2009, 1069/2009, 142/2011; European Commission, 2009, 2011).

The best survival, growth rate, and chemical composition of the larvae are ensured by designing a balanced diet based on nutrient values and protein content. For these reasons, BSFL production has become a flexible technology, able to relate to various food production realities and consequently to their by-product streams (Singh & Kumari, 2019; Barbi et al., 2020; Gligorescu et al., 2022). In this context, the potential use of local residues for BSFL plants presents an opportunity to strengthen the economy and increase the resilience of both the food and insect industries. Indeed, the biotransformation of residues by BSFL minimizes the disposal cost associated with materials and simultaneously creates new value (protein, fat, and frass) that can be incorporated into the material flow in animal feed and agricultural sectors. The present research is specifically focused on the Italian scenario, with a more detailed examination of the northern area, where the largest BSFL full-scale plant is located, already operating based on the utilization of vegetal discharges for insect rearing adopting a modular production system.

As suggested by Jouan et al. (2020), modular production systems are useful to maintain physical barriers, reducing disease spread. This also allows us to have greater control over the risk of the escape of larvae and flies. In the case of escape, this would result in a mere economic loss without negative effects on the environment and the ecosystem since BSF is non-pathogenic, not a vector of disease (Čičková et al., 2015), and requires precise ranges of temperature and humidity to live. This is the first research to investigate the availability (type and quantity) of agri-food by-products in a specific area (100 km), aiming to evaluate the feasibility of establishing a particular industrial activity focused on waste stream valorization. The aim is to create a proximity-insect farming site where various stakeholders (suppliers, producers, and final consumers) collaborate to create a local activity based on circular economy principles.

By creating a database of available agri-food residuals in the area, including their quantity and seasonality, this case study investigates the possibility of closing the material loop with km-0 principles. The objective is to achieve the optimal economic and material value of available by-products through efficient insect rearing practices. Moreover, this research provides the foundation to expand the concept of innovative agri-food by-product valorization and value creation to other Italian regions and European areas in the wake of the continuous improvement of material valorization practices.

2. Material and method

2.1. Inventory of the residues and management system of the agri-food industry near the e BSFL plant

The aim of the study is to investigate the availability of potential by-product supplies for a specific insect-production site (BSFL-plant). Consequently, a reference point was chosen, represented by the first and only industrial-scale production facility located in northern Italy, the company named "BEF Biosystems" (Casalnoceto, AL, Piedmont, Italy) (Fig. 1). A database was created to identify agri-food residues within a maximum distance of 100 km from the BSFL plant, covering the Italian provinces of Pavia (Lombardy Region) and Alessandria (Piedmont Region). Geographic proximity is relevant to create a local system of exchanges for flows and materials. According to regulations CE 1069/2009 and 999/2001, only vegetable-based production and transformation activities were considered for the survey. Following the data of Atlante dell'agricoltura italiana, (2014), we identified the main categories of food production and representative transformation categories in the area: fruit/vegetable cultivation and transformation, cereal production, and transformation.

Considering these activities, a total of 115 companies within a radius of 100 km were selected for the study through internet and website consultation.

The companies were divided into categories: Brewery Industry – BRE; Rice Company - RIC; Wine-making Industry – WIN; Fruit and Vegetable Production and/or Transformation Center - FRU-VEG, Milling – MIL; and Distillation – DIS. Furthermore, they were classified into two sizes (Small-Medium - SM and Large - L) based on the annual production capacity BRE: 10 tons ww/y; MIL: 1300 tons ww/y; FRU-VEG: 200 tons ww/y; RIC: 30 tons ww/y, WIN: 65 tons ww/y; DIS: 150 tons. In addition, companies were classified into three distance ranges from the insect production plant: 0–30 km (B1), 31–60 km (B2), and 61–110 km (B3), using Google Maps data from 2021 (Fig. 1).

For each company, information characterizing the activity was collected through phone calls and/or email, facilitated by the availability of the manager. Data were recorded regarding the productive vocation, type and seasonality of agri-food residues, the estimated annual quantity of residues, and the current biomass management system.

The current biomass management system was registered as "Scenario 0", with responses grouped into the following categories: internal circular economy (CE), Agricultural/Zootechnical exploitation in third-part companies (AGR), and waste collection (WA). Moreover, the nutritional value of the main categories of by-products available in the area was obtained from bibliographical sources (website: Feedepedia, consulted in March 2023).

2.2. Data analysis and statistical evaluation

Using the information collected through direct contact with the companies, the data were processed to present them uniformly and coherently, referring to the production year. Subsequently, the data were aggregated by production type and company size. Based on this information, potential projections for the utilization of by-products were generated, using basic calculation methods (average values, percentages).

2.3. Investigation of nutritional needs of insects and reference's diet formulation

Based on the dietary requirements of the BSFL full-scale plant and

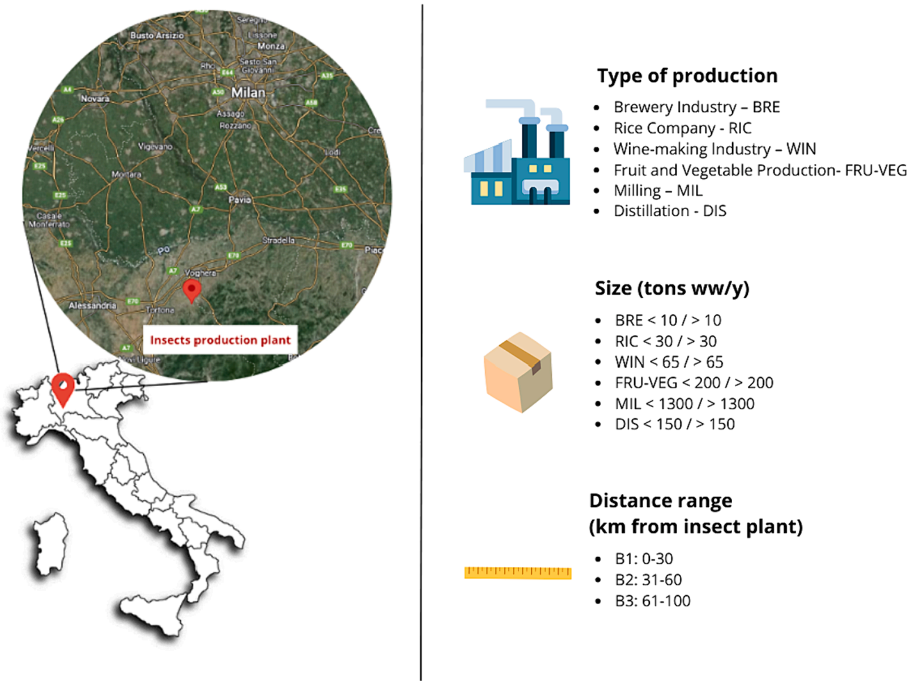

Fig. 1. Geographical indication of the area (North Italy, Google Maps, 2024) and method of classifying the food producer companies under analysis.

consulting scientific papers on this topic (Manurung et al., 2016; Spranghers et al., 2017; Barragan-Fonseca et al., 2018; Lalander et al., 2018; Meneguz et al., 2018; Bava et al., 2019; Danieli et al., 2019), the nutritional needs of BSFL during the fattening phase were analyzed. the nutritional needs of BSFL during the fattening phase were analyzed.

This information served to design the optimal diet for the insect. With this basic knowledge, along with data on available by-products and seasonality, two prototype diets were formulated and evaluated as theoretically suitable for BSFL farming, specifically designed for winter and summer conditions, respectively.

2.4. *Alternative way of local by-products management thought BSFL production*

In order to improve the utilization of the by-products in the area by incorporating insect-rearing, a plan was developed for the utilization of available materials in this context. The plant “BEF Biosystems” was considered a potential user of by-products.

The site has a potential production of 400 tons wet weight (ww/y) of live BSFL, which can be consequently treated as dry or frozen forms for applications in the pet food market, poultry, and aquaculture. A similar quantity of 400 tons ww/y is recovered for the frass, intended for the fertilizer sector. The actual feedstock, which amounts to at least 2000 tons ww/y, consists of vegetal residues from the food industry in North Italy, mainly potatoes, onions, and brewery products.

The substate now in use allows for satisfying rearing performance and welfare of the larvae, verified daily by visual analysis and the weight of the larvae’s samples.

The self-sustainability of the plant above mentioned was projected by applying the winter/summer diets (see 2.3) and considering the use of the residues from local food industries. This projection was referred to as “Scenario BSFL”, where a part of the agri-food biomass is diverted to insect farming.

A comparison between “Scenario 0” (see 2.1) and “Scenario BSFL” was carried out, evaluating the different economic outcomes as well.

2.5. *Larvae and frass chemical characterization*

To clearly characterize the rearing activity, a fraction of BSFL and frass of the full-scale plant production “BEF Biosystems” was characterization at the DISAA lab (University of Milan). The dry matter (DM) and ash content were detected using standard methods (European Committee for Standardization, 2011). The total nitrogen (N) was detected using an elementary analyzer (Elementar Rapid Max N exceed), based on the analytical method of combustion “Dumas” and equipped with a thermal conductivity detector (TCD; Papa et al., 2022). The crude protein (CP) content was calculated by multiplying the total N concentration by the nitrogen-to-protein conversion factor 4.67, according to Janssen et al. (2017). The determination of neutral detergent fibre (NDF), acid detergent fibre (ADF), and lignin (ADL) was performed by following the Van Soest procedure (Van Soest et al., 1980), and the fraction amounts were gravimetrically determined (Papa et al., 2022). The total lipids were determined using the Bligh and Dyer method modified by Papa et al. (2022). The lipids were successively esterified following the Sigma Aldrich Fatty Acid Methyl Ester Preparation Protocol and used for GC–MS analysis (Papa et al., 2022). The content of the total phosphorous (P), K, Ca, Mg, Na, and heavy metals was determined by inductively coupled plasma mass spectrometry (Varian, Fort Collins, USA), preceded by acid digestion (EPA, 1998) of the samples (larvae and frass). Standard samples (from the National Institute of Standards and Technology, Gaithersburg, MD, USA) were run with the samples to ensure precision in the analyses. All analyses were performed in triplicate.

3. Results and discussion

3.1. *Inventory of agri-food by-products in the area and current management*

The 115 potential suppliers of insect-producing plants identified in the area of interest are presented in Table 1 and Fig. 2, respectively.

Out of the 115 selected companies, 102 responded. The response rate was influenced by the sector, ranging from 61 % for DIS to 91 % for WIN, resulting in an average response rate of 76 %.

Table 1
Inventory of vegetal food industries in the vicinity of an insect-production plant and residue production.

	Total number of industries	Number of companies of small –medium and large dimension		Residues production at the different distance from insect production (ton/y)			Time of production	Current ways of management (tons/year)			
		Small-medium	Large	B1	B2	B3		CE	AGR	CE + AGR	WA
BRE	20	8	6	8	6	10	Jan – Dec	0	233.4	0	11.8
Beer malt				1.5	0	0.0					
Threshers of beer				30.0	65.5	176.6					
MIL	10	2	6	2	3	6	Jan – Dec	0	81,225	0	0
Bran				25	15,000	31,012					
Wheatmeal				0	31,000	4188					
FRU-VEG	20	16	1	14	4	3	Jan – Dec	0	0	0	
Damaged tomato, onion, march fraction, salade				190	0	1000					1190
RIC	20	5	4	2	16	5	Jan – Dec.	305	200	20.5	0
Green and red grains				0	240	0					
Husk				0	250	0					
Chaff				0	10	3.5					
Rice straw				5	0	8					
Breaking rice				0	240	0					
WIN	22	14	5	16	7	0	Aug – Jan	20	166	243.2	0
Lees				77	15	0					
Stalks				30	10	0					
Pomace				339.8	51.5	0					
DIS	10	3	1	2	6	5	Aug – Jan	0	3710	0	0
Waste liquids				0	60	0					
Exhausted pomace				0	3650	0					
Tot.	102			44	42	29					

BRE = brewery industry, MIL = milling company, FRU-VEG = Fruit and Vegetable production and/or transformation center, RIC = Rice company, WIN = Wine-making industry, DIS = Distillation Company, B1, B2, B3 = distance of 0–30 km, 30–60 km, 60–90 km from insect-plant respectively, CE = internal circular economy, AGR = Agricultural/Zootechnical exploitation in third-part companies, WA = Waste collection.

Fig. 2. Distribution of each agri-food company' categories (BRE, MIL, FRU-VEG, RIC, WIN, DIS) based on three geographic distance categories (B1 = 0–30 km, B2 = 31–60 km, B3 = 61–100 km), in relation to the insect rearing plant. BRE = brewery industry, MIL = milling company, FRU-VEG = Fruit and Vegetable production and/or transformation center, RIC = Rice company, WIN = Wine-making industry, DIS = Distillation Company.

The highest number of industries was found in the BRE sector (24), followed by RIC (23), WIN (23), and FRU-VEG (23). A lower number of production industries was identified for MIL and DIS companies (13 and 11, respectively). Based on the data, the total production of residual biomass in the area was 87.325 tons per year. This was mainly due to MIL (93 % of the total residues per year) and DIS (4.25 % residues per year). The same proportion was found when calculating residue production for each sector. Upon analyzing MIL, it was found that the bran and the wheatmeal were the most abundant (57.2 % and 40.3 % residues per year of the whole area), followed by mixed products of FRU-VEG and exhausted pomace of DIS.

The RIC sector had the highest number of residues due to the complexity of the industrial transformation. Conversely, a simpler process or no transformation (i.e., BRE, FRU-VEG) resulted in fewer residues. Regarding plant size, the BRE sector was mainly made up of small production sites with fewer residues. Seasonality played a significant role in limiting the residue production of the WIN and DIS between August and January, whereas continuous production was observed throughout the year for the other sectors. However, there are some differences in terms of composition for the FRU-VEG transformation due to seasonal production. The production sites showed a different geographical distribution (Table 1), with WIN and FRU-VEG having the highest number of activities in B1 (distance of 0–30 km from the insect plant), while RIC and DIS were mainly in B2 (distance of 31–60 km from insect plant) and MIL in B3 (distance of 61–90 km from insect plant).

The different geographical vocations of the area seemed to be one of the most important factors that determined the distribution of the activities strictly linked to cultivation, such as RIC and FRU-VEG, or due to transformation activities of the local agricultural products, such as MIL and DIS, where a gradient of distribution occurred. In contrast, BRE had an almost constant distribution throughout the entire territory considered. The most prevalent option for managing residues, applied by 43 % of the companies, is represented by agricultural and/or zootechnical exploitation by third-party companies (ARG), proper re-use (CE; over 30 % of the companies), or again, a combination of CE + AGR. This data corresponds to 98.6 % of the total residues that were primarily destined for the agricultural sector.

The surveyed residues were used for agricultural purposes such as animal husbandry (cattle, pigs, and horses), field fertilization, transfer to feed mills, and transfer to distilleries in the case of by-products represented by vinification marc. In addition, some companies indicated the application of raw residues or composted residues in uncultivated areas within the same company or in the fields. This approach exemplifies the simpler forms of industrial symbiosis, which are based on the principles of (i) re-use as an alternative to waste generation and related costs of management, and (ii) a self-organizing network based on physical proximity and similar manufacturing activities, following a traditional approach (Domenech et al., 2019) yet described for other EU regions.

The remaining fraction currently managed as special solid waste accounted for 1201.8 tons per year (9 % of the total amount) and was limited to the FRU-VEG and BRE sectors. While the BRE strategy was driven by the absence of well-organized waste management due to small and discontinuous production, for the FRU-VEG sector, the decision was influenced by the large volume of product, the scarce quality, and the high biodegradability of the biomass (i.e., rotten or partially damaged fruits and vegetables), which limited long term storage (i.e., odor production, leachate, etc.). The nature and characteristics of this waste were considered similar to those of the organic fraction of municipal solid waste (OFMSW) and were treated in the OFMSW treatment plants to produce mixed compost.

3.2. Nutritional needs of BSFL: Literature review

As indicated in Table 2, an in-depth analysis of diets available in the literature was conducted based on vegetable ingredients. Rather than focusing on individual ingredients, the aim was to obtain a balanced proportion among the macromolecular fractions to support larval growth, merging different nutritive sources. As indicated in the reference offered by Barragan-Fonseca et al. (2019) the sum of CP + NFC in the range of 45 %–89 % DM was strictly linked to larval performance, larval body composition, and fecundity, while the ratio CP:NFC tested in the range of 1:1.5 to 1:5.5 was identified as a key parameter that influenced the protein (42 % DM) in the larvae (Barragan-Fonseca et al., 2019). It was identified as an average characterization of a “Literature Standard Diet” for our research (CP + NFC = 72 % DM and CP 17, NFC 55, CP:NFC = 1:3; Table 2).

As additional data, the macromolecular composition of the BEF Biosystems plant was studied, now composed of vegetal by-products collected throughout northern Italy (Table 2). Mainly, it was composed of fruit and vegetables, contributing to the fiber, non-fiber carbohydrates (NFC) (easily digestible carbohydrates), and brewery residues that are rich in crude protein (CP) content (Table 3).

The “Literature Standard Diet,“ compared to the “full-scale plant’s diet,” had a lower content of NFC and ratio CP:NFC but similar values in terms of CP + NFC. Upon examining the other diets presented in Table 2, which predominately consisted of peel and teguments, they were all characterized by low contents of both NFC and CP, showing a reduction of –23.6 % and −8.7 % of the NFC and CP of the optimal diet, respectively. Consequently, they had a lower value of NFC + CP, indicating reduced nutritional capability. However, they displayed an almost satisfying value of NFC:CP, an indicator of a well-balanced composition. For the present study, the “Literature Standard Diet” was considered a suitable starting point for the subsequent evaluation. In future research, to enhance the NFC content, ingredients rich in sugars and polysaccharides, such as pasta, cereal, and sugar transformation, may be considered (Barbi et al., 2020; Gligorescu et al., 2020).

3.3. Local agri-food by-products, from waste to a diet for BSFL

Following the analysis, the objective is to propose a diet for BSFL, theoretically formulated based on the by-products available in the surveyed territory.

A total of 15 surveyed residues were identified, all suitable to be utilized as ingredients in the BSFL diet following EU regulation (European Commission, 2001, 2009). The chemical composition of these residues is presented in Table 3. Some residues from the cereal industry present a high fiber content with limited nutritional and protein contents. Moreover, rice discharged due to non-standard quality had a nutritional content very similar to that of the final food, as did the residues from the FRU-VEG sector. Only the residues derived from the fermentation for beer and wine production showed significant protein content, while only the wheat meal had a very balanced composition in terms of CP + NFC and CP:NFC of an optimal diet of BSFL (Table 3).

Based on the macromolecular composition of the “Literature Standard Diet” (see 3.2; Table 2) and by considering the availability and seasonality of agri-food residues (Table 1), two diets (summer and winter) have been formulated. The goal of providing the insect-rearing plant with 1000 tonnes of biomass per year to be transformed was reached (Table 2).

3.4. Alternative way of local by-products management thought BSFL production

The FRU-VEG and the BRE generate waste, incurring an economic cost for the current biomass management at 80 Euro/tons ww, estimated at 80.000 and 944 euro/year, respectively.

FRU-VEG sector is widely distributed in the territory, and often a relevant quantity of by-products can be collected, even from a single large production center. However, these biomasses do not maintain a constant composition in macromolecular terms, making it challenging to valorize them in traditional systems. On the contrary, they are easily exploitable as insect rearing substrates. Taking the production site under analysis as an example, the BEF Biosystems company collects the ingredients for the current diet from North Italian food industries. These materials are exchanged without charge and in some cases, transportation costs were waived due to mutual collaboration agreements. The estimated cost of transportation was less than 10 Euro/ton for distances lower than 100 km, reaching a cost of 15–20 Euro for distances of 150–200 km (Fava et al., 2013). The management of agri-food biomasses in traditional ways, as already used by producers (Table 1), was defined as Scenario 0.

On the contrary, focusing on insect rearing and applying the “Scenario BSFL”, a significant portion of the agri-food biomasses available in the analyzed territory could be utilized for insect rearing (700 tons/year of FRU-VEG and 272 tons/year of BRE residues, Fig. 3).

Redirecting the destination of these biomasses, the amount of biomass currently managed as organic waste in the area can be minimized, resulting in a reduction of −52 % waste/year (624 tons /year), which corresponds to a reduction of waste from 84 % to 19 % for FRU-VEG. With respect to Scenario 0, which employed the residues for composting and agricultural uses, Scenario BSFL integrated the management through insect rearing. In this way, it is possible to cut the cost of biomass management for the BRE and FRU-VEG from 116.248 euros to 46.160 euros per year, saving 60 % of the cost. Circular bioeconomy enhances the cascading use of biomass both in terms of the number of bio-based productions (material and energy) and/or the maintenance of its economic value to develop a gainful local economy, improving its resilience (Stegmann et al., 2020). Moreover, the different ways of economical valorization of the biomasses (2000 tons ww) were considered.

Composting (biomass = 60 % w/w of the starting composting biomass, yield of conversion = 25–35 % w/w) led to the production of 500–833 tons w/w of mixing compost destined above all for field agricultural use as an amendment that corresponded to an economic value of 3,000–5,000 euros (value of 6–7 euros/ton w/w). The BSFL plant produces larvae (value of 500 euros/ton w/w) for feed and frass (90 euros /ton w/w) (BEF Biosystems, 2023). The sum of the production generated in “Scenario BSFL” given as whole data is 236.000 euros/year, which means an increase of + 47 fold the value of Scenario 0 and results in the most profitable solution (Craig Sheppard et al., 1994; Diener et al., 2011;

Table 2
Formulation and chemical characterization of BSFL diets based on vegetable products and corresponding larval growing performance as reported in the literature.

Diet	Composition	DM	Ash	CP	EE	NDF	NFC	ADF	CP: NFC	CP + NFC	WRI	SR	ECD	Larval wet weight
	% ww		% DM								g/d	Final/ initial number of larvae	% diet	(n = 10)
Diet based on vegetal food residues (%ww)	(1) 100 % maize distillers	94.9	5.40	29.5	11.1	36.7	17.3	Nd	1:1.7	46.8	3.01 ± 0.06	–	0.25 ± 0.01	0.98 ± 0.01
	(2) 68 % ground barley; 20 % wheat bran; 12 % dehydrated alfalfa	87.1	2.4	11.1	4.0	13.6	68.9	9.6	1:1.22	80	–	0.66 ± 0.03	–	1.332*
	(3) 16 % ground barley; 50 % wheat middling; 10 % dehydrated alfalfa; 24 % wheat straw	89.5	4.1	11.2	4.4	29.2	51.1	19.6	1:4.56	62.3	–	–	–	0.999 *
	(4) 15 % ground barley; 55 % wheat middling; 30 % dehydrated alfalfa	88.2	4.1	13.8	4.0	22	56.1	11.6	1:1.59	69.9		0.67 ± 0.04		1.129 *
	(5) 100 % grinded rice straw	–	–	–	–	–	–	–	–	–	0.58 ± 0.01(a) 0.45 ± 0.01(b) 0.34 ± 0.01(c) 0.44 ± 0.01(d) 0.24 ± 0.01(e)	51.2 ± 2.29 (a) 74.2 ± 2.62(b)80.9 ± 1.19(c) 91.8 ± 1.17 (d)98.3 ± 1.13(e)	9.92 ± 0.01(a) 5.69 ± 0.01(b) 5.67 ± 0.01(c) 6.11 ± 0.01(d) 10.8 ± 0.01(e)	–
	(6) 43.4 % celery; 28.9 % oranges; 27.7 % peppers	8.27	9.11	12.0	2.60	17.8	58.5	11.0	1:4.88	70.5	3.2 ± 0.26	–	0.07 ± 0.01	–
	(7) 47.8 % apples; 15.5 % oranges; 13.8 % apple leftovers; 7.1 % strawberries; 4.8 % mandarins; 4.1 % pears; 3.4 % kiwis; 1.9 % bananas; 1.6 % lemons	13.2	3.04	4.60	2.78	13.9	75.6	9.11	1:16.44	80.2	3.2 ± 0.41	–	0.05 ± 0.011	–
	(8) 100 % winery by-product	35.8	10.3	11.7	7.90	56.6	13.4	46.2	1:1.14	25.16	2.4 ± 0.32	–	0.06 ± 0.002	–
	(9) 100 % brewery by-product	23.2	3.98	20.1	8.67	44.7	22.6	22.5	1:1.13	42.6	5.3 ± 1.05	–	0.14 ± 0.34	–
	(10) 100 % vegetable waste	12.7	10.8	8.6	2.1		44.9	–	1:5.22	53.5	–	–	–	–
	(11) 53.6 % DDGS (dried distiller's grains with soluble); 34.0 % grape pulp; 12.4 % cellulose	72.1	–	17	6.9	–	30	–	1:1.76	47.0	–	–	–	–
	(12) 44.5 % DDGS; 31.2 % potato peels; 24.2 % cellulose	69.9	–	17	5.3	–	30		1:1.76	47.0	–	–	–	–
	(13) 32.4 % DDGS; 44 % bean seeds; 1.5 % sunflower oil; 22.1 % cellulose	92.9	–	17	5.9	–	30	–	1:1.76	47.0	–	–	–	–
	(14) 37.2 %DDGS 24.7 % cabbage	55.4	–	17	4.8	–	30	–	1:1.76	47.0	–	–	–	–

(*continued on next page*)

Table 2 (*continued*)

Diet	Composition	DM	Ash	CP	EE	NDF	NFC	ADF	CP: NFC	CP + NFC	WRI	SR	ECD	Larval wet weight
	leaves 16.0 % old bread22.0 % cellulose													
Literature standard diet	(average composition ± st. deviation)	57.2 ± 34	5.91 ± 3.25	15.5 ± 7.89	5.22 ± 3.36	23.9 ± 9.2	40.6 ± 19.9	13.0 ± 4.5	1: 2.8 ± 1.79	65.9 ± 12.4	–	–	–	–
Current full-scale plant diet	potatoes, onions, and brewery products***	65 ± 5	6 ± 1	13.5 ± 3.53	3.5 ± 1.41		54 ± 8.48		1: 4.22 ± 1.73	67.5 ± 12.0	–	–	–	–
Scenario BSFL. Winter diet comp. (% ww)	70 % fruit and vegetable; 12 % wheat bran; 10 % brewery exhausted cereals; 8 % wheat meal.	30.5	5.10	14.6	3.72	30.4	46.1	9.71	1:3.15	60.7	–	–	–	–
Scenario BSFL. Summer diet comp. (% ww)	58 % fruit and vegetable; 18 % pomace; 10 % exhausted pomace; 4 % Brewery exhausted cereals; 5 % wheat bran; 5 % wheat meal	29.3	6.21	12.8	4.47	36.6	39.8	–	1:3.1	52.7	–	–	–	–

CP = crude protein; CF = crude fiber; EE = ether extract; NDF = neutral detergent fiber; ADF = acid detergent fiber. WRI = Waste reduction index; SR = Survival rate; ECD = efficiency of conversion of digested food. Diet reference: (1) (Bava et al., 2019); (2, 3, 4) (Danieli et al., 2019); (5) (Manurung et al., 2016), (6, 7, 8, 9) (Meneguz et al., 2018), (10) (Spranghers et al., 2017), (11, 12, 13, 14) (Barragan-Fonseca et al., 2018); (15) (Lalander et al., 2018).
*values calculated as larval weight.
**value calculated as larval survival.
***average of three vegetable-based diets covering 1 year of production.

Table 3
Chemical composition of the industrial categories and their by-products available on the territory.

	residues's type	Reference number (2017/107 CE)	DM % ww	ash	CP	EE	CF % DM	NDF	NFC*	ADF	CP + NFC	CP: NFC
BRE	Spent yeast (dehydrated)	*13.1.14*	93.6	7.0	48.9	2.4	1.8	8.8	32.9	2.5	81.8	1:0.7
	beer malt (fresh)	*1.12.13*	24.1	3.3	20.3	7.0	17.6	65.1	4.3	26.4	24.6	1:0.21
	threshers of beer (fresh)	*1.12.12*	24.9	4.1	25.9	6.7	16.4	49.6	13.7	20.8	39.6	1:0.53
MIL	Wheat bran	*1.11.7*	87.0	5.6	17.3	3.9	10.4	45.2	28	13.4	45.3	1:1.62
	Wheatmeal	*1.11.6*	90	3.3	16.0	3.9	–	23.5	53.3		69.3	1:3.33
FRU-VEG	Mixed fruit-veg (average of diets 6; 7 Table 1)	*13.1.6*	14.9	6.07	8.29	2.69	–	15.9	67.1	10.1	75.37	1:10.66
RIC	chalky grains and grains striated with red (that of broken rice)	*1.6.25*	87.5	1.4	9	1.9	1.6	6.2	81.5	2.1	90.5	1:9.06
	Rice chaff-husk	*1.6.10*	91.9	17.5	3.7	1.5	42.6	67.8	9.5	51.7	13.2	1:2.57
	Rice straw	*6.3.1*	92.8	18.1	4.2	1.4	35.1	69.1	7.2	42.4	11.4	1:1.71
	Broken rice	*1.6.1*	87.5	1.4	9	1.9	1.6	6.2	81.5	2.1	90.5	1:9.06
WIN	lees of vinification data from Rivas et al., 2021	*13.1.14*	9.09	92.3	8.12	3.89	75.6	71.8	4.91	53.5	16.1	1:0.43
	Grape stalks (see: grape branches and leaves)	*13.1.14*	56.3	5.5	4.6	1.7	39.4	48.1	40.1	n.a.	36.9	1:8.72
	Grape pomace (fresh)	*5.25.3*	39.7	8.4	11.8	5.8	25.7	53.8	20.2	n.a.	44.1	1:1.27
DIS	waste liquids of grape pomace distillation	*Not reported*										
	Exhausted pomace of grape distillation (see: silage grape pomace)	*13.1.14*	37.0	7.1	12.9	6.8	27.7	54.2	19	53.3	31.9	1:1.47

DM = dry matter; CP = crude protein; CF = crude fiber; EE = ether extract; NDF = neutral detergent fiber; ADF = acid detergent fiber.
Source: Feedepedia, 2022 except where otherwise specified.
*NFC calculated as (100-ash) – CP-EE-NDF.

Ooninck & Boer, 2012).

As stated by Barragan-Fonseca et al. (2017), the key solution for creating cost-effective and optimized insect rearing on a large scale is to recycle organic resources to add sustainability to the production and valorise locally produced material. This would reduce the cost of the final insect feed, enhance the economic returns from the mass-rearing establishments, and increase production. As is presented in this study, strong cooperation between agricultural production and insect-rearing companies is essential to reach an economic profit on both sides.

3.5. *Proximate and fatty acid compositions of the BSFL from the full-scale plant*

To fully understand the high-quality products that can be obtained through insect rearing, we conducted a chemical evaluation of BSFL and frass deriving from the production plant "BEF Biosystems".

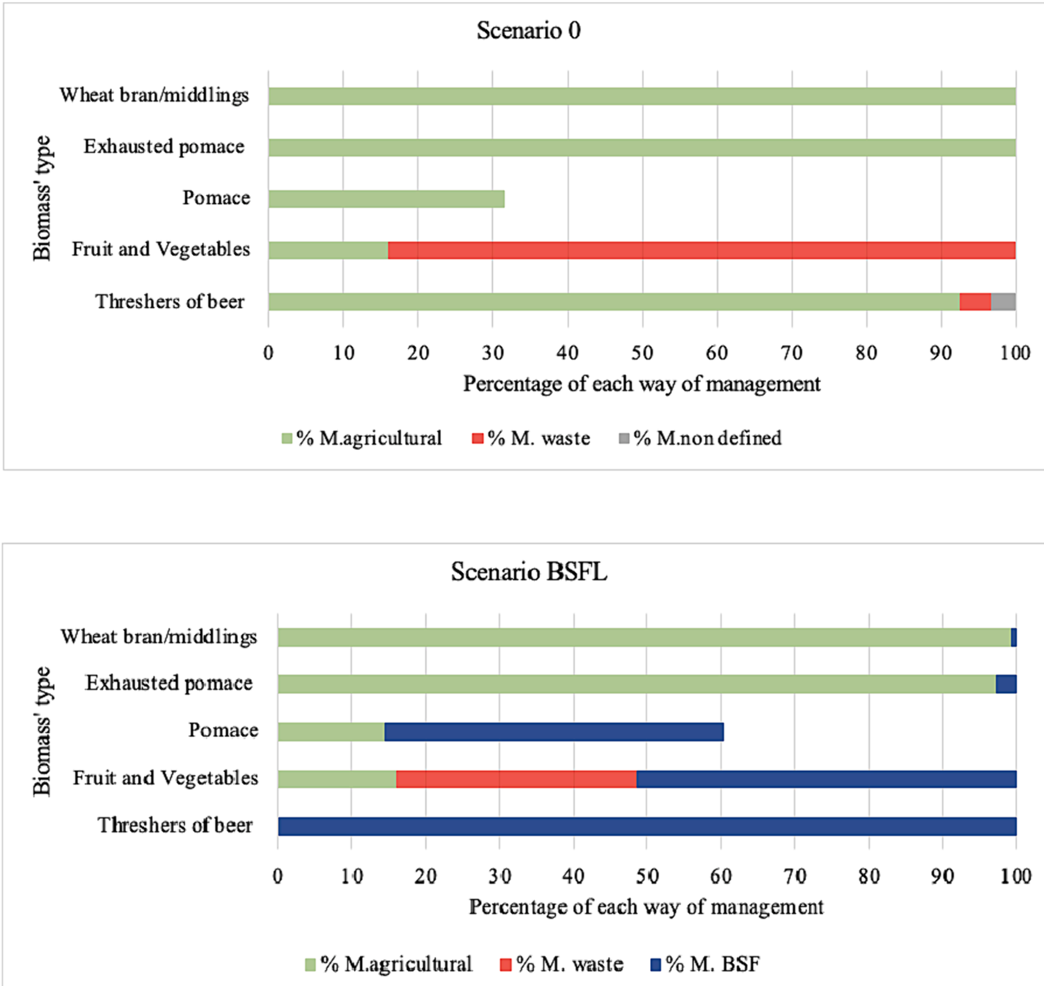

Fig. 3. Ways of biomasses management for the by-products of main interest for insect rearing. Scenario 0 (currently applied) and possible Scenario BSFL respectively. Percentage of management through agricultural way, waste collection, BSF rearing and non-defined in some minorities.

3.5.1. BSF larvae

The chemical composition of BSFL showed a high content of fat (41 % DM) and crude protein (31 % DM) (Table 4). Similar content of CP was found in the literature where comparable rearing conditions were adopted (Meneguz et al., 2018). However, in that case, a lower fat content and a higher amount of fiber were recorded, likely due to better nutrient availability and differences in the rearing scale (lab vs. full-scale plant). The full-scale plant allowed for a more efficient “domestication” of BSFL, promoting better welfare for the larvae through higher rearing densities and precise temperature control. Considering the fatty acid (FA) composition of the larvae, unsaturated FAs were the most abundant, accounting for 52.7 % of total fatty acids (TFA), with a PUFA: MUFA ratio of 2:1. The most prevalent FA is Linoleic acid (26.6 % of TFAs), followed by Hexadecanoic acid (16.6 % TFA) (Table 4).

The content of unsaturated FAs and the PUFA: MUFA ratio are in line with the findings of Jucker et al. (2017), in terms of amount and composition. Interestingly, Meneguz et al. (2018) found a PUFA:MUFA ratio favoring MUFA, although the life stage of the analyzed larvae could have influenced the utilization of fat reserves by the animal, and consequently, its results. Furthermore, the presence of Lauric acid (C12:0) is noteworthy, being the most abundant FA (16.6 % TFA), followed by undecanoic and tridecanoid acids in lower amounts. The C12:0 content is significantly lower compared to the results of the data of 41.5 % TFA and 52 % TFA in BSFL reared on vegetable substrates (Jucker et al., 2017; Meneguz et al., 2018). These differences can be explained by the fact that insects can synthesize certain FAs *de novo*, such as Lauric acid (C12:0), Myristoleic acid (C14:1), Palmitoleic acid (C16:1), and Oleic acid (C18:1n-9) (Stanley-Samuelson et al., 1988). In addition, the composition of BSFL can be influenced by external factors beyond their diet.

3.5.2. Frass

Frass had a significant content of organic matter, primarily composed of the fiber fraction (Table 5). In addition to the residual undigested material, a portion of the fiber was made from chitin (around 20 % of the total) (Finke, 2007). The C/N value suggested an equilibrated release of the contained nutrients as an amendment in analogy with the mixed compost (Table 5). Moreover, the N and P contents were 2.88 % DM and 1.76 % DM, respectively comparable with those of other organic fertilizers (i.e. poultry manure), becoming a valid alternative to the synthetic fertilizer as urea (Beesigamukamaet al., 2020) (Table 5).

It is relevant to remember the great adaptability of use towards many types of cultivation such as maize, tomato, lettuce, etc. (Anyega et al., 2021; Beesigamukama et al., 2020; Dzepe et al., 2022). Then, by using very clean biomass for insect rearing, it is guaranteed to have a very high heavy metal content in comparison to poultry manure. Moreover, as an additional positive aspect, insect frass can also be applied in organic cultivation systems (European Parliament, 2018). It is important to note the versatility of frass for various types of cultivation, including maize, tomato, lettuce, and others (Anyega et al., 2021; Beesigamukama et al., 2020; Dzepe et al., 2022). Moreover, using clean biomass for insect rearing ensures a lower heavy metal content compared to poultry

Table 4
Black soldier fly larvae chemical composition (full-scale plant production).

Parameter	Unit measure	Value (average ± standard deviation)
DM	% ww	30.5 ± 0.93
Ash	% DM	7.66 ± 0.31
CP*		31.4 ± 0.4
CF		41.8 ± 0.11
NDF		32.8 ± 0.23
ADF		22.8 ± 1
ADL		13.6 ± 2.2
P	g kg^{-1} DM	7.46 ± 0.23
Mg		2.88 ± 0.05
K		11.3 ± 0.20
Ca		13.8 ± 0.20
Na		0.8 ± 0.020
Fe	mg kg^{-1} DM	280.0 ± 51.0
Cu		13.3 ± 0.60
Zn		119.8 ± 14.7
Mn		130.4 ± 2.2
Decanoic acid, methyl ester	% Fatty acid content	1.73 ± 0.42
Undecanoic acid, methyl ester		5.79 ± 0.09
Dodecanoic acid, methyl ester		11.8 ± 0.23
Tridecanoic acid, methyl ester		3.37 ± 0.01
Myristic acid, methyl ester		4.42 ± 0.03
Myristoleic acid, methyl ester		2.23 ± 0.23
Pentadecanoic acid, methyl ester		0.22 ± 0.01
cis-10-Pentadecenoic Acid, methyl ester		10.3 ± 0.11
Hexadecanoic acid, methyl ester		16.6 ± 0.64
Palmitoleic acid, methyl ester		2.29 ± 0.12
Heptadecanoic acid, methyl ester		0.51 ± 0.01
cis-10-Heptadecenoic acid, methyl ester		0.52 ± 0.02
Stearic acid, methyl ester		2.25 ± 0.12
Elaidic acid, methyl ester		1.32 ± 0.06
Oleic acid, methyl ester		1.05 ± 0.02
Linolelaidic acid, methyl ester		2.39 ± 0.12
Linoleic acid, methyl ester		26.6 ± 0.06
γ-Linolenic acid, mehyl ester		1.87 ± 0.02
α-Linolenic acid, methyl ester		1.81 ± 0.06
Arachidic acid, methyl ester		0.38 ± 0.10
cis-11-Eicosenoic acid, methyl ester		0.51 ± 0.09
cis-8,11,14-Eicosatrienoic + Arachidonic acid, methyl ester		1.77 ± 0.10
Erucic acid, methyl ester		0.25 ± 0.36
∑ saturated FA		47.03 ± 0.02
∑ unsaturated FA		52.7 ± 0.35
∑ PUFA		34.5 ± 0.22
∑ MUFA		18.2 ± 0.13

*data calculated as N*4.67 according to Janssen et al., (2017).
DM = dry matter; CP = crude protein; CF = crude fiber; NDF = neutral detergent fiber; ADF = acid detergent fiber; ADL = acid detergent lignin.

manure. Additionally, insect frass can be applied in organic cultivation systems, which is a positive aspect (European Parliament, 2018).

3.6. Utilization of BSFL and frass to loop the chain value

The BSFL rearing was useful to reduce waste production and increase economic value. The final products could be employed on a local scale, strengthening the resilience of the area by limiting its dependence on inflows and increasing its ability to make more effective use of local resources (Elleby et al., 2021). Since BSFL is suitable as an ingredient for feed production, as an applicable case study for this article, the laying hens' sector has been taken into consideration. In traditional rearing systems, birds were used to eat insects and consequently express their natural instincts, so the utilisation of live BSFL in this sector is the most immediate way of doing so.

Following the suggestions of Tahamtani et al. (2021) to substitute 10 % to 20 % ww of laying hens' diet with live BSFL and knowing that the average feed consumption for laying hens over 100 weeks of production is estimated to be 68.9 kg per animal (Farmstocking, 2023), it's possible to calculate an average consumption of BSF live larvae of 7 and 14 kg/bird/productive cycle, respectively.

Table 5
Chemical characteristics of Black soldier fly frass (full-scale plant production).

Parameter		Frass
DM	% ww	54.1 ± 1.10
Ash	% DM	9.64 ± 1.16
VS		90.36 ± 1.05
C		52.5 ± 0.60
C/N		18.2
NDF		55.7 ± 1.86
ADF		35.4 ± 0.45
ADL		14.8 ± 0.49
N		2.88 ± 0.09
$N\text{-}NH_4$		0.40 ± 0.01
P_2O_5		1.76 ± 0.14
K_2O		1.72 ± 0.09
Pb	mg kg^{-1} DM	0.35 ± 0.04
Cd		0.10 ± 0.02
Ni		3.49 ± 0.39
Zn		88.2 ± 3.70
Cu		18.9 ± 1.20
Cr tot		4.62 ± 0.45
As		0.19 ± 0.03

DM = dry matter; VS = Volatile Solids; C = Carbon; C/N = Carbon/Nitrogen; NDF = neutral detergent fiber; ADF = acid detergent fiber; ADL = acid detergent lignin; N = Nitrogen.

Considering the annual larvae production of this case study (400 tons/year), it would be possible to feed for one productive cycle more than 57,000 and 28,000 animals, respectively (BEF Biosystems, 2023).

These data highlight the positive effects that can be achieved through the insect bioconversion of waste material. Similar considerations could also be applied to the other feed sectors mentioned above. Moreover, it is possible to modify and tailor the production systems to suit the specific features and needs of the area.

Considering the frass, this material has an N content that could be applied organically as a substitute for mineral nitrogen fertilizers. With a special focus on maize fertilization (i.e., one of the cultivations with a higher N requirement), Tanga et al. (2022), hypnotized fertilizing maize (*Zea mays* L.) with sole BSF frass, introducing 2.8 tons/ha, which is equivalent to 100 kg N/ha. Alternatively, a combination of BSF frass (50 % of the required N, 1.4 tons/ha of frass) with mineral NPK fertilizer (50 % of the required N, 294 kg/ha of NPK) was considered. Having in mind the annual frass production of the insect rearing plant "BEF Biosystems", would be possible to fertilize an area of around 142 ha (100 % frass) or 285 ha (50 % frass + 50 % NPK).

4. Conclusion

The study highlights the positive effect generated by the exploitation of agri-food by-products operated by insect-rearing plants. This is a zero-waste process that generates BSFL and frass as outputs, which can be efficiently reintegrated into local production systems as sustainable sources for the feed and agricultural sectors. The results suggest the possibility of creating a material loop, offering advantages for all the stakeholders involved in this innovative activity. The scalability and replicability of these investigations make them applicable to other geographical regions, both within Italy and worldwide, promoting similar circular valorisation of biomasses.

In the future, if an update on the legislative framework occurs, the investigation of other by-product types (animals' origin, catering waste) as insect rearing substrates will be necessary. In this case, it may be necessary to understand if thermal pre-treatment of the materials is needed to make them stable and lower the bacterial load. In light of this knowledge, this will help to expand even more the efficiency of biomaterial valorisation.

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CRediT authorship contribution statement

Arianna Cattaneo: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Marco Meneguz:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Data curation. **Sihem Dabbou:** Writing – review & editing, Validation, Conceptualization. **Fulvia Tambone:** Writing – review & editing, Investigation. **Barbara Scaglia:** Writing – review & editing, Validation, Methodology, Investigation, Conceptualization.

Declaration of competing interest

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

Data availability

The data that has been used is confidential.

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