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A mobile black soldier fly farm for on-site disposal of animal dairy manure

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Abstract

Black soldier fly (BSF), *Hermetia illucens* (L.) (Diptera Stratiomyidae), is a saprophagous insect that is receiving a growing scientific and economic interest since during the larval stage it is extremely voracious and able to consume a wide range of organic materials. This ethological characteristic is particularly suitable for waste management at industrial scale. The extraordinary ability to accumulate high levels of proteins and lipids, allows the use of resulting larvae as animal feed or biodiesel production; the residue of the bioconversion process, that consists of larval frass and not converted organic matter is assimilable to organic fertilizer. The aim of this study was to evaluate the bioconversion process by black soldier fly larvae (BSFL) on fresh and mature dairy manure. A "mobile bioconversion unit" that works as a mobile breeding unit was used, allowing to carry out bioconversion tests directly on fields, in different livestock farms located on the Basilicata territory (Italy). Total larval and frass biomass, bioconversion yield, BSFL development time and substrate reduction were evaluated for each treatment. All the analysed parameters differed from the control (larvae fed in standard diet) but not between the two substrates from the zootechnical chain. Although development time significantly differed across treatments, BSF correctly grow and reduce all substrates confirming larvae can be used to bioconvert animal manure reducing the undesired effects occurring from mismanaged this kind of substrate.

Key words: black soldier fly, bioconversion, circular economy, substrate reduction, environmental pollution.

Introduction

Nitrous oxide (N_2O), methane and ammonia (NH_3) production from manure is the second largest cause of greenhouse gas (GHG) emissions on dairy farms after enteric methane (CH_4), and it represents the 7% of N_2O and CH_4 emitted in agriculture (Aguirre-Villegas *et al.*, 2016). The impact of non-correctly treated manure is surely noxious for the environment. Moreover, the methane produced by the storage of manure under anaerobic conditions, has a 21 times higher impact than carbon dioxide (Rico *et al.*, 2015). Nowadays, the most common practices for manure management, in accordance with environmental laws, are outdoor storage on heaps, anaerobic digestion or composting (Tittonell *et al.*, 2010; Arriagada *et al.*, 2019; Ndambi *et al.*, 2019). However, if manure is not managed properly, it might lead to the spreading of pathogens, unpleasant odours, GHG emissions and air and ground water pollution, especially in low- and middle-income countries (Aguirre-Villegas *et al.*, 2016; Lim *et al.*, 2016). The situation will be aggravated with the rapid growth of the world population, which is estimated to reach 9.7 billion in 2050 (Surendra *et al.*, 2016), resulting in an increase in livestock farms to meet the pressing rising of nutritional demands. A very urgent need is linked to the possibility to dispose of this waste in a sustainable way.

In natural systems, manure and other decaying organic materials are degraded by several microorganism and organisms, including the black soldier fly larvae (BSFL), *Hermetia illucens* (L.) (Diptera Stratiomyidae) (BSF) (May, 1961; Lardé, 1990; Myers *et al.*, 2014). This species can digest pig (Sheppard *et al.*, 2002), chicken (Bondari and Sheppard, 1981), and dairy manure (Myers *et al.*, 2014). BSFL are able to decompose decaying organic materials (food waste, rotting fruit manure, etc.). During the bioconversion process, BSFL feed on manure by transforming it into more valuable biomass (larval biomass rich in proteins and lipids), reducing this substrate of 50-60% or more (Myers *et al.*, 2014; Zhou *et al.*, 2013). As an added benefit, while larvae eating, they aerate and dry it, reducing odours (Newton *et al.*, 2005). The presence of BSFL in poultry and swine manure also strongly reduces the development of the house fly, *Musca domestica* L. (Diptera Muscidae) (Abd El-Ghany, 2020). Another feature of the BSFL-mediated bioconversion process is related to the digestion of microorganisms of which this substrate is rich and the production of antimicrobial and antifungal compounds (Landi, 1960; Hoffmann and Hetru, 1992; Natori, 1995; Sherman *et al.*, 2000) that can modify the microflora of manure, reducing damaging and displeasing species (Erickson *et al.*, 2004). Indeed, it has been reported that BSFL, rich in antimicrobial peptides (Manniello *et al.*, 2021; Moretta *et al.*, 2020; 2021; Di Somma *et al.*, 2022), can also specifically reduce *Escherichia coli* and *Salmonella enterica* in chicken and cattle manure (Erickson *et al.*, 2004; Liu *et al.*, 2008) and in human feces (Lalander *et al.*, 2013).

Organic waste from the agrifood chain are used to produce a valuable insect biomass in the form of protein and fat sources to be used in the animal feed industry. In particular in Europe, in accordance with European regulations (EU Reg. 1069/2009; EU Reg. 68/2013; EU Reg. 893/2017; EU Reg. 1017/2017 and EU Reg. 2021/1372) only seven insect species, including BSF, can be reared for usage in aquaculture and poultry and pig farms (Abbasi and Abbasi, 2016; Makkar *et al.*, 2014; Sanchez-

Muros *et al*., 2014). Other categories of waste, including manure, in Europe are not allowed as substrates to obtain feed (Rumpold *et al*., 2017), but insect fractions can be considered for non-food applications: indeed, the high quantity of lipids can be exploited for biodiesel production (Zheng *et al*., 2012; Li *et al*., 2015; Leong *et al*., 2016) and cosmetic application (Verheyen *et al*., 2018), chitin and chitosan could be used in different applications in the medical, cosmetical, pharmaceutical (Park and Kim, 2010; Hahn *et al*., 2020; Triunfo *et al*., 2021), food, textile fields and wastewater treatment (Hamed *et al*., 2016), and larval frass (a combination of uneaten substrate, feces, and exuviae) can be used in crop fertilization (Setti *et al*., 2019; Poveda, 2021).

For these reasons, the breeding of BSF as bioconverter insect is receiving great attention from a scientific and economic point of view. Moreover, insect farms have a lower environmental impact, indeed, requires less water and emits lower levels of greenhouse gases and NH_3 compared to classical livestock (Oonincx and de Boer, 2012; Van der Spiegel *et al*., 2013; Rodríguez-Miranda *et al*., 2019). The bioconversion process is a potentially valuable solution for issues of global interest: environmental pollution, waste disposal and the rise of the global food demand which will dramatically increase (Tilman *et al*., 2011; Salomone *et al*., 2017).

In this work a "mobile bioconversion unit" was used. It consists of a wagon in which temperature and humidity are controlled by a thermostat and a humidifier, that keep the BSFL rearing conditions stable. In this wagon it is possible to have a maximum of 6 boxes of substrates on which BSFL are reared. This wagon can be moved to different livestock farms to evaluate the bioconversion process of manure directly on fields. In this project, the wagon stayed in zootechnical farms located on the Basilicata territory (Italy) with the aim of demonstrating to farmers an alternative solution for the management and disposal of these substrates. For each bioconversion cycle, on fresh and mature dairy manure and control diet, the total larval and frass biomass, bioconversion yield, BSFL development time and substrate reduction were evaluated.

Valorisation of manure using insects represents a sustainable solution that is part of a circular economy (Rumpold *et al*., 2017); indeed, starting from a waste of zootechnical farms (dairy manure), a very poor feeding substrate in term of economic and biological value, the bioconversion process managed by BSFL close the circle given valuable products such as insect meal and organic fertilizer (larval frass). Although the potential of BSFL for bioconversion of livestock manure is widely described (Diener *et al*., 2009; Zhou *et al*., 2013; Lalander *et al*., 2015; ur Rehman *et al*., 2017), with this research the opportunity to dispose of these by-products of the zootechnical chain directly on fields was highlighted, with the potential to offer an immediate solution to the farmers. Moreover, the high number of used larvae open the ways to the industrial use of BSFL, as mostly studies at benchtop scale are performed so far.

Materials and methods

Insect rearing

Black soldier fly eggs were collected from a colony maintained in the Laboratory of Physiology and Molecular Biology of Insect, at University of Basilicata (Italy). They were stored in 500 ml clean glass jars in an environmental chamber at 27 ± 1 °C, 70% relative humidity (RH) until hatching. After hatching, about 10,000 neonate larvae for each replicate, were placed into plastic boxes containing 7.0 kg of Gainesville diet, consisting of 30% alfalfa, 50% wheat bran, 20% corn meal at 70% moisture, with 13.60% of proteins, 3.5% of lipids, 6% of ashes and 13.90% of fibres. On the fifth day, that is considered the first day of the bioassay, larvae were transferred into plastic boxes containing 7 kg of each substrate. A group of larvae was transferred into plastic boxes containing Gainesville diet used as control. Prior to the transfer, 10 groups of 10 larvae of each box were randomly selected and weighted to assure that their weights were not significantly different.

Two types of manure were used as substrate: mature dairy manure and fresh dairy manure respectively provided by "Azienda Tamburrino Antonio" and "Azienda Tamburrino Mariano", both situated in Oppido Lucano (Potenza, Italy). Plastic boxes with larvae were placed in the "mobile bioconversion unit", an insulated compartment, consisting of all the equipment indispensable to maintain the same environmental conditions of the previously described environmental chamber, that allowed to carry out bioconversion trials in two different livestock farms located on the Basilicata territory (Italy).

For each treatment 3 replicates were carried out.

Dry matter

Dry matter of substrate was calculated at the beginning of the experiment for manure samples and at the end of the experiment for larvae and frass. Samples were firstly weighed, dried for 48 hours at 55 °C in a Gallenkamp Hotbox Oven (London, UK) and then re-weighted. Dry matter was determined according to the following equation:

1) Dry matter (%) =
$$\frac{\text{Final weight (g)}}{\text{Initial weight (g)}} \times 100$$

Larval and frass biomass

The bioassay was stopped when the first pre-pupae were observed, with the characteristic darker cuticle colour (Meyers *et al*., 2008; Ewusie *et al*., 2019), and their moving away from the feeding substrate. Larval frass were manually sieved to separate larvae from frass. Larval and frass biomasses were weighed separately.

Bioconversion yield

Bioconversion yield identifies the results of the bioconversion process in terms of total larvae dry matter. This parameter allows to evaluate the conversion from substrate to a high value product as larval meal consists of protein, lipids, minerals and chitin. Bioconversion yield was determined according to the following equation:

Table 1. Dry matter of substrate, larvae and frass. Dry matter of each substrate was measured at the beginning of the experiment applying the equation 1. Dry matter of BSFL and frass were measured at the end of the experiment applying the equation 1. Data are presented as mean ± SE (n = 3). Statistical analysis was performed with one-way ANOVA (analysis of variance) and Tuckey *post-hoc* test. Different letters indicate significant differences among groups (Substrate p = 0.0030, Larvae p = 0.0116, Frass p < 0.0001).

	Standard	Mature	Fresh
Substrate	29.14 ± 0.83 %^{a}	30.66 ± 0.21 %^{a}	22.85 ± 1.47 %^{b}
Larvae	33.69 ± 1.11 %^{b}	30.96 ± 0.40 %^{b}	35.44 ± 0.31 %^{a}
Frass	38.20 ± 0.33 %^{c}	50.23 ± 0.38 %^{b}	53.07 ± 0.27 %^{a}

2) Bioconversion yield (g) =

$$\text{Final weight (g)} \times \frac{\text{Dry matter (\%)}}{100}$$

Substrate reduction

Substrate reduction was calculated following methods contained in Tschirner and Simon, 2015, applying the equation:

3) Substrate reduction (%) =

$$\frac{\text{Initial substrate (g)} - \text{Frass (g)}}{\text{Initial substrate (g)}} \times 100$$

Statistical analysis

The hypothesis of normality has been checked with standard Shapiro-Wilk test. However, given the limited number of replications available for each experiment, also non-parametric tests were considered for both comparisons of mean (Kruskal-Wallis) and homogeneity of variance (specifically, both Bartlett and the modified Levene tests were applied). Then, substrate, larval and frass dry matter, development time, larval and frass biomass, bioconversion yield and substrate reduction were analysed by one-way analysis of variance (ANOVA) and Tuckey *post-hoc* test. Statistical results are reported in supplemental material tables S1, S2, S3. Statistical analysis was performed with the R software.

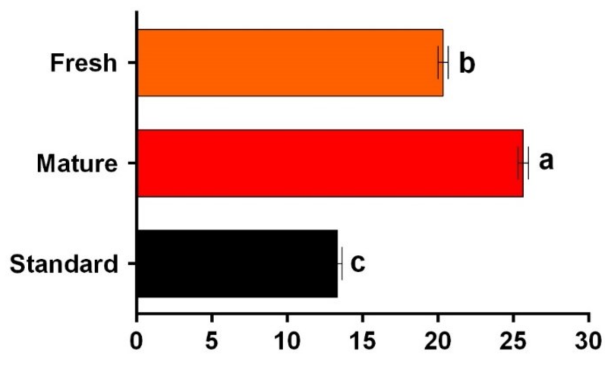

Figure 1. Development time (days) of BSFL fed on different substrates (Control diet, Mature dairy manure and Fresh dairy manure). The development time of each replicate was evaluated from the first day of the trial to the first observation of the pre-pupal stage. Data are presented as mean ± SE (n = 3). Statistical analysis was performed with one-way ANOVA and Tuckey *post-hoc* test. Different letters indicate significant differences among groups (p < 0.0001).

Results

Substrate, larval and frass dry matter

Dry matter of control diet and mature manure differed from dry matter of fresh manure (table 1) (df = 2; $F_{2,6} = 17.71$; p = 0.003). Larval dry matter differs between larvae fed on standard diet/mature manure and fresh manure (table 1) (df = 2; $F_{2,6} = 10.24$; p = 0.0116), while dry matter of frass differs among all the analysed samples (table 1) (df = 2; $F_{2,6} = 577.6$; p < 0.0001).

Larval analysis

The development time statistically differs among samples fed on different substrates (figure 1) (df = 2; $F_{2,6} = 344.3$, p < 0.0001). Control larvae completed the larval stage in 13-14 days after eggs hatching with a development time lower than the other substrates (figure 1). Larvae fed on different kinds of manure from the dairy farms completed larval stage in a range of 20-26 days after eggs hatching, reaching the pre-pupal stage with delay respect to control larvae: 20-21 days for larvae fed on fresh manure, 25-26 days for larvae fed mature manure (figure 1).

Although the starting weight of larvae did not statistically differ among different treatments (supplemental material tables S1-S3), larval total biomass differs among substrates of the zootechnical chain and standard diet, as the standard diet is complete in all nutrients and assure a better development and weight gain of the larvae (figure 2) (df = 2; $F_{2,6} = 71.56$, p < 0.0001): 2.83 ± 0.10 kg for larvae fed on standard diet, 1.84 ± 0.07 kg for larvae fed on mature manure and 0.95 ± 0.09 kg for larvae fed on fresh manure.

Bioconversion yield is 0.98 ± 0.04 kg for larvae fed on standard diet and 0.57 ± 0.02 kg and 0.34 ± 0.04 kg of larvae fed on mature and fresh manure, respectively (df = 2, $F_{2,6} = 80.79$, p < 0.0001) (figure 3).

Frass total biomass and substrate reduction

The weight of the frass statistically differed among treatments (df = 2; $F_{2,6} = 235.4$, p < 0.0001), with the lowest frass biomass for the sample derived from larvae fed on control diet (2.06 ± 0.05 kg), compared to frass from larvae fed on mature (3.35 ± 0.03 kg) and fresh (2.89 ± 0.05 kg) manure (figure 4) that also showed the highest substrate reduction (standard diet = 70.52 ± 0.70%; mature manure = 52.14 ± 0.41%; fresh manure = 58.67 ± 0.67%) (figure 5) (df = 2; $F_{2,6} = 235.4$, p < 0.0001).

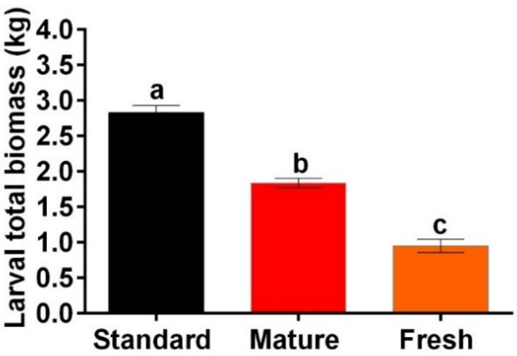

Figure 2. Larval total biomass (kg) of BSFL fed on different substrates (Control diet, Mature dairy manure and Fresh dairy manure). Total biomass weight of BSFL was measured at the end of the bioconversion experiment, manually separating larvae from frass. Data are presented as mean ± SE (n = 3). Statistical analysis was performed with one-way ANOVA and Tuckey *post-hoc* test. Different letters indicate significant differences among groups ($p < 0.0001$).

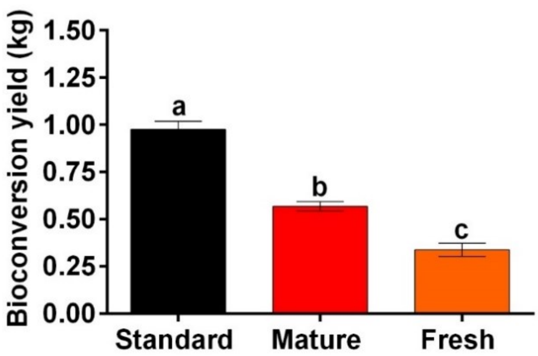

Figure 3. Bioconversion yield (kg) of BSFL fed on different substrates (Control diet, Mature dairy manure and Fresh dairy manure). Dry biomass weight of BSFL was measured at the end of the experiment applying the equation 1. Biocoversion yield was calculated applying the equation 2. Data are presented as mean ± SE (n = 3). Statistical analysis was performed with one-way ANOVA and Tuckey *post-hoc* test. Different letters indicate significant differences among groups ($p < 0.0001$).

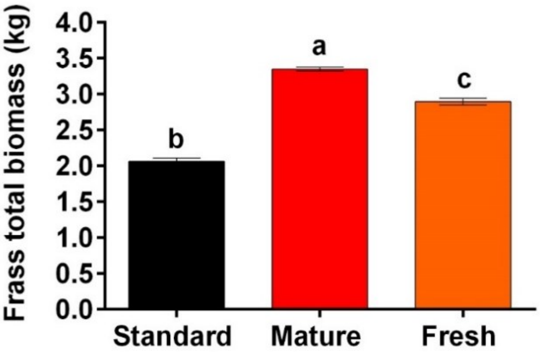

Figure 4. Frass total biomass (kg) derived from BSFL fed on different substrates (Control diet, Mature dairy manure and Fresh dairy manure). Total weight of frass was measured at the end of the experiment, manually separating frass from larvae. Statistical analysis was performed with one-way ANOVA and Tuckey *post-hoc* test. Different letters indicate significant differences among groups ($p < 0.0001$).

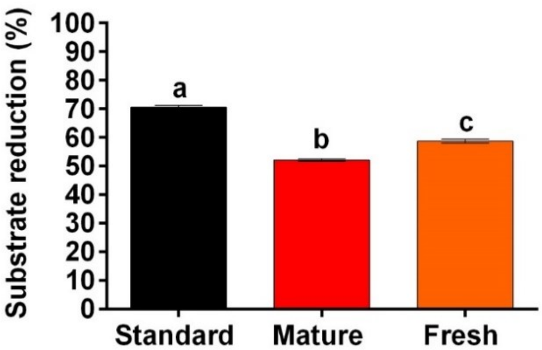

Figure 5. Substrate reduction after BSFL feeding on different substrates (Control diet, Mature dairy manure and Fresh dairy manure). Substrate reduction was calculated at the end of the experiment, applying the equation 3. Statistical analysis was performed with one-way ANOVA and Tuckey *post-hoc* test. Different letters indicate significant differences among groups ($p < 0.0001$).

Discussion

BSF is a saprophagous Diptera, able to feed on several decomposing organic materials, both of animal and vegetable origin (Bava *et al*., 2019; da Silva and Hesselberg, 2020) such as by-products from agrifood chain (Nguyen *et al*., 2015; Jucker *et al*., 2017; Scala *et al*., 2020), spent grains (Webster *et al*., 2016; Ruhnke *et al*., 2018; Scala *et al*., 2020) and many others including manure (Sheppard, 1983; Newton *et al*., 2005; Zhou *et al*., 2013; Myers *et al*., 2014; Bortolini *et al*., 2020).

BSF has become one of the most important insects in the world for bioconversion of organic waste. Bioconversion is a biological process by which some organisms, including insects, convert organic materials into secondary products of high biological value or even energy sources (Maurya *et al*., 2021). BSF can be considered a real scavenger of organic matter: generally, females, attracted by specific volatile organic compounds (Scieuzo *et al*., 2021; Nardiello *et al*., 2022), oviposit on or near decaying organic substances, and after hatching, the larvae feed on them until the prepupal stage (Hoc *et al*., 2019). Environmental conditions and substrate characteristics are very important for efficient bioconversion (Tschirner and Simon, 2015; Cammack and Tomberlin, 2017). The ideal substrate moisture is around 60% (Diener *et al*., 2011) and the optimum range of temperature is 27-32 °C (Tomberlin and Sheppard, 2002; Tomberlin *et al*., 2009). Under the rearing conditions of 28 °C and 75% RH and with Gainsville diet as feeding substrate, the total life cycle lasts 20-35 days (Zhou *et al*., 2013). Furthermore, BSFL can reduce the original substrate up to 50-80% (for example faecal sludge, livestock manure, fruit and vegetable waste) (Diener *et al*., 2011; Zhou *et al*., 2013; Barragan-Fonseca *et al*., 2017; Jucker *et al*., 2020).

Also, in our experiment, BSFL were able to correctly feed on the two dairy manure substrates, grow and reduce them, even if their development time was significantly extended compared to the standard diet, that is complete in all nutrients and represents the control. The development time of larvae fed on manure was highly extended compared to larvae fed on Gainesville diet (20-26 days for manure, 13-14 days for control diet). Fresh manure could be more suitable thanks to a greater humidity content, indeed the development of BSFL resulted more rapid, even if with a lesser consumption of the substrate and a minor achievement of nutrient compared to mature manure. Indeed, larvae reached a final total larval biomass of 0.95 and 1.84 kg, on fresh and mature dairy manure respectively, while larvae growth on control diet achieved a final total biomass of 2.83 kg. Although the best performance is achieved on standard diet and all the analysed parameters of larvae fed on control diet are superior compared to those obtained on larvae fed on manure, the experiment shows the great potential of BSFL in bioconvert the provided feed. Dairy manure has a similar content in nutrients (11% proteins, 4% lipids) compared to standard diet (Gold *et al*., 2020), so the delay of the larvae development and the slow weight gain could be ascribed to the not full availability of the substrate for the larvae in terms of correct digestion of this feeding substrate that could be related to a high fibre content (Wen *et al*., 2004): cellulose, hemicellulose and lignin content could reach the 80% in fresh manure and 65% in mature manure (Li *et al*., 2011a; ur Rehman *et al*., 2017).

Our results are similar with those obtained by Myers *et al.* (2014) for prepupae reared on dairy manure but in small-scale setup (i.e., lower number of larvae per replicate: 300 4-day-old larvae for each replicate). Specifically, Myers *et al*. (2014) tested two different quantities, 0.08 g/larva and 0.23 g/larva each day: the development time (26-30 days) was higher than our results, with a longer time for larvae fed with the least amount of manure. Despite the longer development time, larvae fed with less manure were able to reduce a higher percentage of substrate. For this reason, it is important to correctly balance the amount of feed for the number of larvae, to obtain the best performances in terms of development time and weight gain. Comparing our results with those obtained by Miranda *et al.* (2020) in a study with a similar scale setup (10,000 4-day-old larvae) in which larvae are fed on dairy manure with 72% of moisture, a shorter development time of larvae were detected: 16 days. Chemical and physical qualities of manure can differ, even within the same type, and this could influence time of development and weight gain.

Overall, our results show that manure can be a good substrate for BSFL development and, thanks to their ethology, BSFL are able to reduce the initial substrate biomass by 52-59%, which is almost at maximum range of values reported for pig (29-53%), chicken (32-62%), and cow (35-58%) manure (Zhou *et al*., 2013). Our research demonstrated that BSFL represents a useful tool to manage dairy manure, strongly reducing its initial biomass and favouring its total recovery and transformation in larval biomass and a fertilizing-like compounds, consisting of larval frass, undigested substrate, and chitin (Poveda, 2021).

This study is part of a project focused on the sustainable valorisation of dairy farm waste (manure), using the bioconversion process mediated by BSFL. The project aims to exhibit the practicality of organic waste management by BSFL, specifically manure, through a “movable unit of bioconversion”. This unit is a mobile farm to use directly on field, at livestock farms, exploiting the extraordinary bioconversion abilities of the BSFL. Further studies are necessary to evaluate this process on other zootechnical waste directly on field. Indeed, the process of rearing BSFL on manure from dairy production could decrease the ecological impact of the zootechnical sector (Oonincx and de Boer, 2012; Dobermann *et al*., 2017).

Currently, also a great interest is related to high quality secondary products, obtained at the end of the bioconversion process: proteins that could be used for innovative bioplastics (Setti *et al*., 2020), chitin that could be used in different fields, including agricultural, cosmetic, pharmaceutical fields (Zainol Abidin *et al*., 2020), and the bioconversion residue, made of frass and not converted organic matter, that is similar to organic fertilizer (Setti *et al*., 2019). It shows a great potential for improving soil fertility and therefore it is suitable for crop fertilization, as a valid alternative to chemical fertilizers, taking also into account the sanitary risk related to the pathogenic microorganisms in manure (Choi *et al*., 2009; Green and Popa, 2012; Lalander *et al*., 2013). Indeed, BSFL are able to reduce the bacterial load of some pathogens, decreasing the risk of disease transmission to animals and humans when the bioconversion residue is used as fertilizer (Lalander *et al*., 2013). In addition, the possibility of extracting lipids that could be used in cosmetic field (Franco *et al*., 2022) or to produce biodiesel from larval biomass represents a good alternative to the use of classical raw materials, such as starch, vegetable oils (rape, sunflower, macadamia or others) or animal lipids (Li *et al*., 2011b; Nguyen *et al*., 2018; Franco *et al*., 2021). Indeed, the biodiesel derived from the rapeseed has 4.3% of saturated fatty acids, contrarily to the one derived from BSFL that has 67.6% of saturated fatty acids (Li *et al*., 2011a; Nguyen *et al*., 2018). Due to its ability to efficiently convert organic waste into lipid-rich biomass, BSFL is considered a promising biodiesel feedstock (Wong *et al*., 2019). The use of carbon sources and agricultural ground exclusively for fuel production, rather than for food industry, appears to be currently unsustainable.

Definitely, our preliminary results on dairy manure, part of a bigger project of valorisation of waste derived from livestock farms, confirm that this substrate is a good source for development of BSFL to obtain a value product to place directly on the market: larval frass. Meanwhile, the reduction of waste substrate and its recovery are to be considered as important results of the bioconversion process by BSFL, helping to reduce the undesired effects occurring from mismanaged manure, that represents a primary problem for the farmers.

The bioconversion process by BSFL could represent an interesting solution, in terms of environmental and economic safeguard, which fully embraces the concept of circular economy. Further studies will be carried out to evaluate the effect of bioconversion on other kinds of manure or digestate derived from biogas plants. These findings could avoid the use of common practices for waste management and specifically for manure (outdoor storage on heaps, anaerobic digestion or composting)

(Tittonell *et al*., 2010; Arriagada *et al*., 2019; Ndambi *et al*., 2019) that if not properly managed, it might lead to an increase of greenhouse gases emissions, air, ground, and water pollution, and others secondary effects such as spread disease and unpleasant odours.

Conclusions

In this work the performances of BSFL on two kinds of dairy manure were analysed. Although this substrate has similar content in nutrients compared to standard diet, and BSFL probably don't entirely gain nutrients due to the high content of fibre, and their growth performances on this substrate are worst compared to performances on standard diet, BSFL are able to properly feed and dispose of it, obtaining larvae rich in lipids, as reported by Franco *et al*. (2021; 2022), that can be used in cosmetic and bioenergetic fields and frass that can be used for organic agriculture. With the bioconversion process, it is possible to handle this waste in an unconventional way that represents a perfect example of circular economy and sustainability. Moreover, the "mobile bioconversion unit" is an added value to the project because it allows to exploit BSFL potential directly on the field, with a view on industrial scale breeding.

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AF, CS, RS, contributed equally to this work. Conceptualization, PF; Data curation, AF, CS, RS; Methodology: AF, CS, RS; Project administration, PF; Supervision, PF, SM; Writing - original draft, AF, CS, RS, SM, PF; Writing - review and editing: AF, CS, RS, IMM, DC, SM, PF.

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