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ORIGINAL PAPER

Blatticomposting of Food Waste, Production Estimates, Chemical Composition and CO_2 Emissions Savings: A Case Study

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Abstract

Half of the organic waste generated by mankind is compostable. Many of the traditional methods of food waste treatment generate pernicious effects on ecosystems, such as leachates, greenhouse gases, pathogenic microorganisms or odors. Three cockroach species that are widespread as live food for feeding exotic animals (mainly reptiles) due to their high growth rates, waste consumption, production and quality of blatticompost: the Madagascar hissing cockroach (*Aeluropoda insignis* Butler), the Guyana spotted cockroach (*Blaptica dubia* Serville) and the ivory cockroach (*Eublaberus sp.*) has been evaluated. Neither the weight–length ratios (W–L) nor the body condition index (K_{rel}) of the three species studied were statistically different between the control and organic waste treatment groups. Average intakes *per animal per day* were 0.93 g in *Aeluropoda*, 2.22 g in *Blaptica* and 2.58 g in *Eublaberus*. Blatticompost production rates were 0.11, 0.75 and 0.52 g / animal*day, respectively. Taking into account the differences in size and density of individuals, this implies an average waste consumption of 1015.9 g/m^2*day, of which 26.7% would be transformed into blatticompost considering the three species together. This is equivalent to 304.8 mt/ha*month of food waste recycled, a blatticompost production of 81.4 mt/ha*month and an estimated greenhouse gas emission savings of 817.2 mt/ha*month. Results indicate that any of the three species studied would be a viable alternative, although the ivory cockroach (*Eublaberus sp.*) presents ideal characteristics. The massive use of this species in the large-scale treatment of organic waste is proposed. Given the enormous advantages of this treatment and the zero environmental costs (absence of invasive character) could be necessary to adapt the legislation of the European Community to include blatticomposting as a suitable waste treatment as it is done in other parts of the world.

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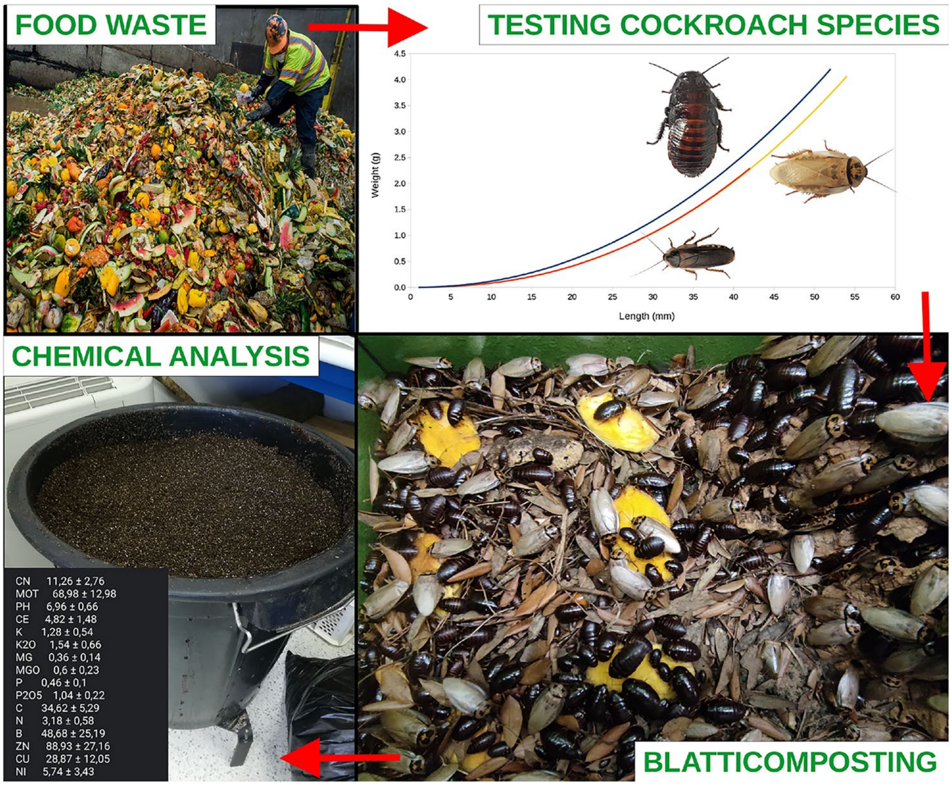
Graphical Abstract



Keywords Blatticomposting · *Blaptica* · *Aeluropoda* · *Eublaberus* · Food waste · Greenhouse gas emissions · Bioconversion

Statement of Novelty

Each citizen of the earth produces 74 kg of organic waste *per year* which is responsible for emitting 296 m^3 of greenhouse gases (GHG) into the atmosphere, mainly CO_2, CH_4 and NO_2, if these wastes are not processed. One of the best systems for processing organic waste is composting, but traditional systems also emit some GHGs. Vermiculture is another alternative, but somewhat slow. In the present work food waste consumption by three species of cockroaches commonly used as pets in terrariums is evaluated. This alternative has undoubted advantages on other composting methods. Cockroaches are excellent bioconverters, not very selective, efficient, fast acting and their compost (blatticompost) is excellent. Also, with the blatticomposting GHG emission savings are another point to consider.

Introduction

The Global Problem of Food Waste

At the current rate of human population growth, humanity will exceed 1 billion by 2050, resulting in a 60% increase in food demand [1]. Consequently, the waste generated by human activity will be between 2000 and 3400 million tons in 30 years increasing by 70% in 2050 [2]. Therefore, the World Bank has allocated more than $4.7 billion to more than 340 solid waste management programs in many countries around the world since 2000 [1].

Moreover, organic waste represents 13.8% of global food production and the trend will be increasing so its treatment is one of the most important sustainable development objectives in European countries [3]. In fact, the management of organic waste according to the World Bank's "What a Waste 2.0" report, is crucial to achieve healthy and sustainable human settlements [1]. In this sense, not recycling this waste can generate serious health problems for the population residing near landfills due to the proliferation of pathogenic microorganisms, increased greenhouse gas (GHG) emissions such as CO_2, N_2O and CH_4, infiltration of toxics into groundwater, and loss of quality of life due to increased odors and visual impact of landfills [4]. In addition, organic waste is responsible for 26% of GHG emissions [5].

As emerging countries industrialize and increase their urban population, the problems associated with the lack of treatment of food waste increase considerably. In this regard, 34% of the world's waste is produced by only 16% of the highest income countries. Only these countries have effective organic waste treatment systems, as costly collection, separation and pretreatment infrastructures are required [6]. In fact, in these countries more than one third of their waste is recycled with techniques such as composting or incineration [7]. However, this does not translate into a decrease in waste because greater economic development also leads to a much greater increase in food consumption and a growing diversification of eating habits [8]. In fact, in developed countries, the consumption of meat, precooked products and packaged foods is increasing in the last decades [9]. This type of food waste is more difficult to process and therefore more harmful to the environment [10].

Therefore, after several decades of study and hundreds of cases analyzed, some authors conclude that developing countries generate more food waste in the post-harvest stages, while in developed countries the greatest losses occur in the post-consumption stages [10]. This is due to the lack of storage and preservation technology in the first case and food wastage in the second. Therefore, there is enormous margin for improvement in the treatment of organic waste in all countries of the world regardless of their level of economic and social development. The problem is the same for all, although treatment solutions differ in each case [11].

In addition to these technical aspects, another important factor that is influencing the relentless increase in food waste in recent decades is climate change [12]. In fact, in the medium and long term, significant losses are expected in agriculture, since the water and thermal requirements of many crops are making them unviable in large areas of the planet [13]. In addition to these direct climatic factors, there are indirect effects due to the increase in pests and diseases; the increase in farm expenses due to a greater need for pesticides, fertilizers and irrigation; the consequent abandonment of many farms due to low profitability; changes in supply and demand in local, national and international markets; the gap between the problems caused by global warming and the technical solutions proposed to mitigate it; changes in consumption habits, etc. All these processes will further increase organic waste levels along the entire food chain, from the producer to the consumer and in all countries, over the coming decades [12].

Composting with Insects as a Solution to the Waste Problem

Due to the limitations of traditional vermiculture in hot environments, other composting alternatives based on the use of different insect species are being tested in many Mediterranean climate zones [14]. Insects have great potential due to the enormous diversity of food adaptations they present, their rapid growth, high reproductive rate and ability to tolerate high levels of overcrowding. This allows them to be reared at high densities in confined spaces. In addition, insects generate very few GHGs [15]. Moreover, insects are very rich in highly digestible proteins with a very good amino acid composition. Therefore, they have been used in animal and even human food all over the world [8]. Insects can also be used to produce oils, lubricants, dyes, biodiesel and various pharmacological products [16]. As pointed out [2], humanity is facing an unprecedented biotechnological revolution that integrates environmental stewardship, new forms of highly productive livestock farming and the circular economy.

One of the most commonly used insect species in composting and protein production is the mealworm (*Tenebrio molitor*). Traditionally, this species has been fed a diet based primarily on cereal flours, mainly wheat, oats and barley with vegetable supplements for hydration of the larvae. However, some studies show that the species can degrade wastes as diverse as plastics [17], leachates and solids derived from the olive industry [18], organic garbage [19], coffee grounds [20], etc. An undoubted advantage of mealworm is that the EEC has recently approved its use in human food, which undoubtedly means an upturn for the increase of its industrial exploitation [21].

Composting of miscellaneous organic wastes has also been used extensively with the black soldier fly (*Hermetia illucens*), a species that has high temperature (~28 °C) and lighting (intense blue-white light at least 5 h per day) requirements for reproduction [22]. This species is ideal for composting household waste in tropical and Mediterranean areas due to its adaptability to heat, intense solar radiation and high waste consumption that can exceed three times its weight per day [23].

Although different species of crickets are usually industrially bred for their protein values with a commercial diet based on meal and vegetables, it is no less true that their growth and transformation speed could be useful as waste bioconverters [24]. However, the results are contradictory in stating that they are more selective in their feeding than other insects [25]. One of the most serious problems of cricket exploitation is cannibalism. However, this can be controlled with specific management and good feeding [26]. The bioremediation potential of crickets is complementary to that of other species, since they have a great capacity to digest residues rich in fiber that other detritivorous insects are not very fond of [27].

Finally, cockroaches have also been used in the bioremediation of organic wastes of diverse nature due to their low trophic specificity, adaptability to a wide variety of conditions, high prolificacy, voracity, no need for light and high tolerance to overcrowding [14]. In addition, cockroaches are nutritionally better than other insects due to their high protein levels, good amino acid balance and low fat content [28]. In fact, cockroaches are suitable as bioconverters and, therefore, mentality towards them must change and start considering them excellent candidates for large-scale organic waste recycling [14]. Prejudices towards cockroaches are mainly based on the fact that they can transmit pathogenic microorganisms, although it is necessary to clarify that these are only present in the food they consume when they feed in landfills or sewers [29]. When feeding on organic waste that is only a few days old, the digestive tract of cockroaches is capable of eliminating any pathogenic microorganisms, generating an excellent compost, called blatticompost, which is as innocuous as vermicompost [14].

This work proposes a general methodology to evaluate different cockroach species for their capacity as detritivores. The bioconversion potential of three cockroach species widely used as live food in reptile and poultry farming is explored. The main hypothesis of this research is that the use of these insects for organic waste recycling may be appropriate not only because of their transformative potential, but also because of the low management costs they generate. Results of this paper may contribute to the development of new research and alternatives for the possible use of cockroaches on an industrial scale in the future. Due to the good performance rates in the bioconversion of food waste exposed in this work, to extend the use of these insects in the large-scale recycling of organic waste of a more diverse nature (industrial waste, invasive algae of the genus *Rugulopteryx*, invasive freshwater species such as water hyacinth, manure, etc.) is obligated.

Material and Methods

Cockroach Species Used

The consumption and blatticompost generation rates of three cockroach species: the Madagascar flat hissing cockroach (*Aeluropoda insignis* Butler), the Guyana spotted cockroach (*Blaptica dubia* Serville) and the ivory cockroach (*Eublaberus sp.*) is compared (Fig. 1).

The genus *Eublaberus* is under taxonomic discussion because some authors consider the ivory cockroach as a variant of the six-spotted cockroach (*E.distanti*), others as the true *E.distanti* with the current *E.distanti* being a separate species called *E.bioyelli* [30]. For these reasons, the species used in this work is referred to as *Eublaberus sp.* Ivory until its taxonomic identity is definitively resolved.. The three tropical species investigated were acquired from licensed exotic animal dealers. None of them are protected by the CITES convention, the IUCN or the Spanish Catalog of Threatened Species, nor does their breeding violate the Invasive Species Law (Royal Decree 216/2019, of March 29, BOE-A-2019-4675). The species studied do not have any invasive potential in SW Spain, since they do not reproduce outside the terrarium or even die from desiccation if they remain out of the terrarium for a long time, as has been experimentally proven (personal observations).

Maintenance Conditions

The animals were kept in Exoterra (www.exo-terra.com) terrariums (90 × 45 × 90 cm) with a 15 cm substrate consisting of cypress leaves (Fig. 2). Humidity was regulated by

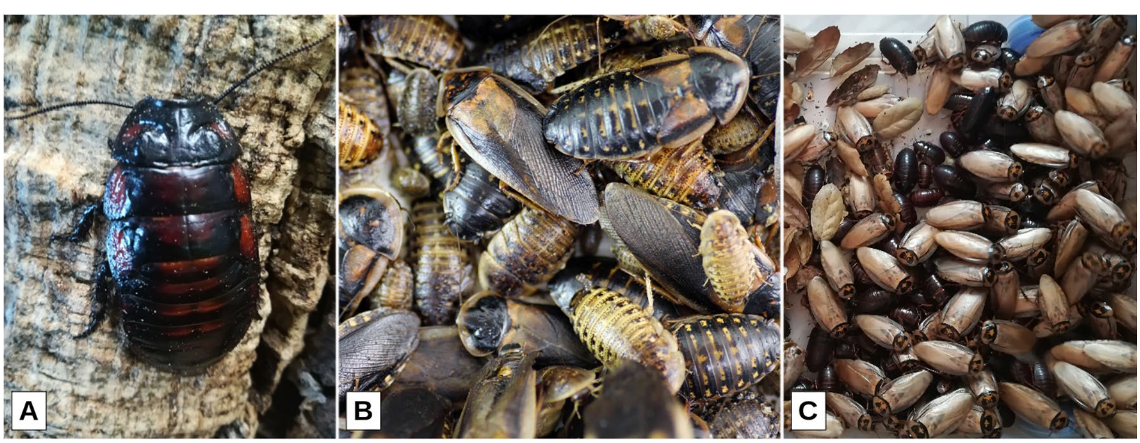


Fig. 1 Species of cockroaches under study. **A**: *Aeluropoda insignis* (male). **B**: *Blaptica dubia* (winged males, females with vestigial wings and nymphs). **C**: *Eublaberus sp.* Ivory (light adults and dark nymphs)

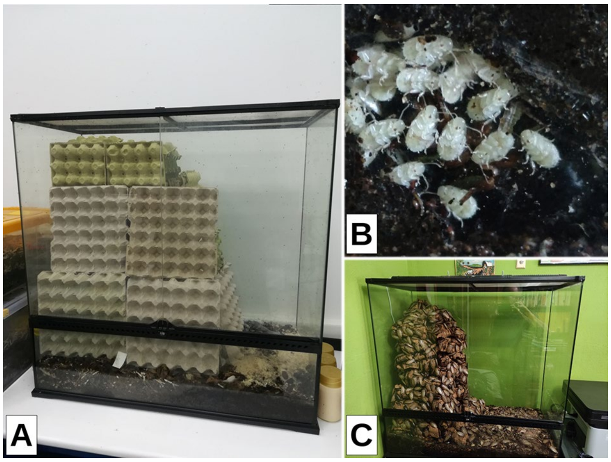


Fig. 2 Maintenance conditions of the control groups. **A**: Terrarium with *Blaptica dubia*. Nymphs (**B**) and terrarium (**C**) of *Eublaberus sp.*

Table 1 Average ± standard deviation humidity and temperature parameters over the five weeks of testing in the terrariums and containers for each species

Species	Humidity (%)	Temperature (°C)
Aeluropoda insignis	72.10 ± 16.57	25.95 ± 0.72
Blaptica dubia	83.75 ± 6.47	27.88 ± 0.49
Eublaberus sp. Ivory	62.31 ± 7.36	25.46 ± 0.39

sporadically hydrating the substrate. For temperature control, a thermal blanket was used with a timer that is activated during the night, which is when the cockroaches remain active. Each terrarium was maintained at the most suitable humidity and temperature conditions for each species according to the information available [29]. To monitor the environmental conditions of the terrariums, humidity and temperature records were taken every two days and averages and standard deviations were calculated over the five-week experimental period (Table 1). *Eublaberus sp.* Ivory requires a drier environment than the other two cockroach species. *B. dubia* has higher temperature requirements and tolerates higher humidity. *A. insignis* has intermediate humidity requirements and tolerates lower temperatures than *B. dubia*. All three species were maintained in the terraria for approximately one year prior to the experiment on a mixed diet of dog food and vegetable peelings before starting the organic waste consumption experiments (Fig. 2). Therefore, it can be concluded that the three species are acclimatized and did not suffer any stress from transport and subsequent captivity, as evidenced by the fact that they reproduced normally in the rearing containers (Fig. 2).

In addition, three batches of 50 animals *per species* were kept in 80 × 60 × 32 cm stackable plastic boxes (www.auer-packaging.com) (Fig. 3). The animals were in all cases adults or big nymphs (of similar size) in the last instars stages to avoid including small nymphs whose trophic behavior is more selective towards a higher protein content [29]. In these batches, feeding was based exclusively on common organic waste such as paper napkins, fruit and vegetable scraps, meat and fish waste, coffee grounds, cooking oil, stale bread, cereals, dog food scraps, guinea pig bedding scraps, cooked food waste, grass clippings and partially composted material. All waste was mixed using an industrial shredder and distributed evenly among the batches. The animals were fed ad libitum, as new material was added when they had consumed all the feed. Feed intake, both in the control group (feed and dog pellets) and in the group based on various organic wastes, was weighed on precision scales. Temperature conditions in the boxes were maintained with heating cables due to the three-dimensional complexity of the structure (Fig. 3). As in the breeding terraria, humidity conditions in the boxes of the experimental batches were maintained by adding water to the substrate. However, hydration was very sporadic, as the stacked design of the boxes allows maintaining a very constant humidity and temperature. In fact, the problem in the stacked boxes is rather one of excess humidity, so that cardboard egg cups, shredded paper and/or wood shavings

Fig. 3 Structure of stackable boxes for testing the consumption of organic waste (**A**), detail of the heating cables (**B**) and interior of the boxes (**C**)

had to be added as absorbent materials to avoid the appearance of mold, which is detrimental to these insects [29].

Measured Parameters

Potential weight–length (W–L) curves [31] were performed with the animals in the rearing terraria, covering the largest possible size range (nymphs and adults) and selecting at least 40 individuals for each species. In this way, it was evaluated whether the body condition of the animals changed with the change of diet [32]. These curves were validated for their coefficients of determination (R^2), root mean square error (RMSE), normality of the residuals according to the Shapiro–Wilk test and homoscedasticity of the residuals according to the Breusch-Pagan test [33]. Possible significant differences in the W–L curves for each species according to diet type and between species were determined by the Kolmogorov–Smirnov test [34]. Equivalent size ranges were used in these calculations to prevent small nymphs, excluded from the experimental batches, from influencing the results of statistical tests. The body condition of the animals (K_{rel}) was determined as the ratio between the observed weight values and those expected by the W–L curves [35]. K_{rel} values before and after the five-week feeding experiment for each species were analyzed by Dunn's test [36].

Food waste consumption and blatticompost production have been estimated at industrial scale (mt/ha) extrapolating the data obtained in the laboratory by a simple change of units. In addition, the current wholesale price of vermicompost has been taken into account as a reference and the blatticompost production data was transferred to gross euros per hectare. As the World Bank states that each citizen of the earth generates 0.71 kg of organic waste *per* day [1], it is possible to determine how much waste *per* inhabitant can be processed in one hectare by blatticomposting. To estimate the greenhouse gas (GHG) emission savings of a hectare subjected to blatticomposting, the analyses of [37–39] and especially the detailed complementary data of these works were taken as reference. These parameters were also analyzed between species using Dunn's test [36].

Three samples of the blatticompost of the three cockroach species (3 × 3) fed with organic residues were analyzed in an agricultural reference laboratory. The parameters measured were: Total organic matter (TOM, %), carbon–nitrogen ratio (C/N), moisture (%), pH, Cation Exchange Capacity (CEC, ms/cm), K (%), K_2O (%), Mg (%), MgO (%), P (%), P_2O_5 (%), C (%), N (%), B (mg/kg), Zn (mg/kg), Cu (mg/kg), Ni (mg/kg) and Cd (mg/kg). The results of these parameters were tested between species using Dunn's test [36].

Results

Both in the terrariums (control group) and in the stackable boxes (organic waste feeding) the animals showed reproduction and growth rates considered standard for the three cockroach species[29].

The weight–length relationships (W–L) of the three species studied were not statistically different between the control group and the organic waste treatment, so both sets of data were pooled for each species. More specifically, the Kolmogorov–Smirnov test to determine the possible differences in W–L curves between diets gave values of D = 0.231 (p-value = 0.887) for *A.insignis*, D = 0.222 (p-value = 0.984) for *B.dubia* and D = 0.081 (p-value = 0.981) for *Eublaberus sp*. Once the data for both diets were pooled for each species, there were also no differences in the W–L curves among the three species (Table 2). Nevertheless, W–L curves were calculated independently for each species to obtain a higher level of precision in future studies (Table 3). In this sense, *A. insignis*, due to its larger size and width, shows slightly higher growth in weight (W) relative to length (L) but is not significantly different from the other two species (Fig. 4, Table 2). In relation to *B.dubia*, this species shows a complete allometric overlap with *Eublaberus sp.* although it reaches shorter lengths. Results indicated that the three W–L curve models are reliable in order to estimate W using L measurements in the three species (Table 3). The values of the coefficient of determination R^2 are high (= 0.98) in *B. dubia* and *Eublaberus sp*. *A.insignis* shows an R^2 = 0.71 which is not so high, possibly due to the great morphological variability of this species in relation to sex and age. Despite this, it is not necessary to perform different equations within this species because the R^2 value is sufficient, there is a great difficulty to delimit the age intervals and it is not possible to identify externally the sex of the nymphs. The F-ratio value of the ANOVA test shows that the variation of W with

Table 2 Results of the analysis of the differences between the W–L curves with the pooled data of both groups of diets and according to the Kolmogorov–Smirnov test (D)

	Aeluropoda insignis	*Blaptica dubia*	*Eublaberus spp*
Aeluropoda insignis	–	D = 0.071, p-value = 0.999	D = 0.071, p-value = 0.999
Blaptica dubia	D = 0.071, p-value = 0.999	–	D = 0.023, p-value = 1.000
Eublaberus spp	D = 0.071, p-value = 0.999	D = 0.023, p-value = 1.000	–

Table 3 Statistics of the W–L (weight-length) equations of the three cockroach species studied

Parameter	*Aeluropoda insignis*	*Blaptica dubia*	*Eublaberus sp. "Ivory"*
W–L equation	$W = 8.26E\text{-}04{*}L^{2.16}$	$W = 3.93E\text{-}04{*}L^{2.32}$	$W = 4.05E\text{-}04{*}L^{2.31}$
R^2	0.71	0.98	0.98
F-ratio	57.78 ***	767.41 ***	692.30 ***
Residual normality	0.96 ns	0.97 ns	0.96 ns
Residual homoscedasticity	1.89 ns	2.19 ns	1.64 ns

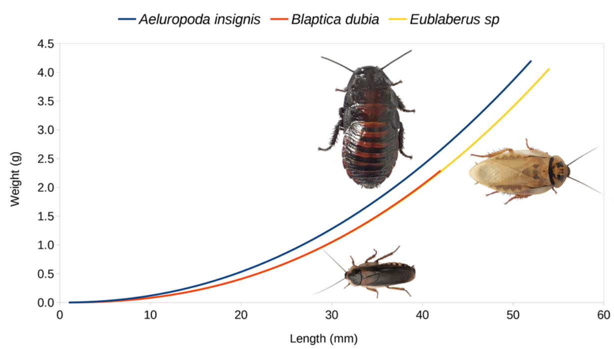


Fig. 4 Weight-length (W-L) relationships in the three cockroach species studied: *Aeluropoda insignis*, *Blaptica dubia* and *Eublaberus sp.* Ivory. Relative sizes are approximate

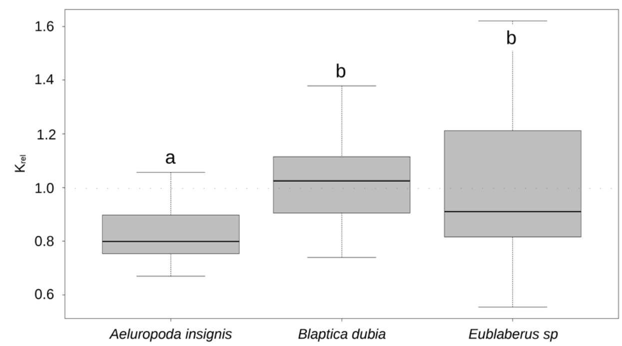


Fig. 5 Boxplots of the body condition index (K_{rel}) for the three species studied. The median or second quartile (Q_2, thick horizontal line), the standard deviation (outside each box) and the range of the variable (ends of the segments) are represented. The horizontal dotted line shows the isometric growth value ($K_{rel} = 1$). Lowercase letters show significant differences from Dunn's nonparametric *post-hoc* test

respect to L is highly significant with respect to the residual variation with p-values < 0.001 in the three species. The Shapiro–Wilk test for testing residual normality showed no significant difference (p-value > 0.05) in any of three species. Also, the Breuch-Pagan test indicates that the residuals present homoscedasticity in the three species (p-value > 0.05), that is, they are similarly distributed along the length of the specimens analyzed (Table 3). Therefore, all statistics used indicate that the three W–L models are very reliable for the analysis of body condition (K_{rel}) and for the determination of W *per* L in the three cockroach species.

The body condition index (K_{rel}) did not reflect differences according Wilcoxon test in any of the three cockroach species between the standard diet groups and the organic waste feeding groups. As statistics were obtained W = 106, p-value = 0.287 for *A.insignis*, W = 54, p-value = 0.258 for *B.dubia* and W = 1565, p-value = 0.406 for *Eublaberus sp*. However, Dunn's test shows significant differences between *A. insignis* and the other two species at the end of the five-week experimental period (Fig. 5). The statistics obtained in the comparison of the three species were Z = − 3.126, p-value = 0.001 between *A.insignis* and *B.dubia*; Z = − 3.060, p-value = 0.001 between *A.insignis* and *Eublaberus sp.* and Z = 1.102, p-value = 0.135 between *B.dubia* and *Eublaberus sp.* As its name indicates, the Madagascar flat hissing cockroach is a species of greater length and width but much smaller body depth. *A. insignis* shows somewhat lower K_{rel} values (Fig. 5), but there is no significant difference between standard diet and organic waste feeding (W = 106, p-value = 0.287). As K_{rel} values are close to 1 in all three species, it follows that under experimental conditions growth is practically isometric. That is to say, none of the three species notably modifies its body condition with respect to the standard diet (Fig. 5). *B. dubia* presents the best mean body condition after the experimental period, concluding that it is the species that best adapts to the food waste diet, although the differences with *Eublaberus sp.* are not really significant as mentioned above (Z = 1.102, p-value = 0.135).

Regarding the consumption rate *per animal per day* of organic residues, there were no differences between both diet groups within each species. Wilcoxon test statistics were W = 13, p-value = 0.2 for *A.insignis*, W = 19, p-value = 0.936 for *B.dubia* and W = 44, p-value = 0.968 for *Eublaberus sp*. However, when grouping both diet groups as one and comparing them among the three species, Dunn's test shows that *A. insignis* is significantly separated from the rest of the species by a lower consumption of organic residues (Fig. 6). The statistics were Z = − 2.73, p-value = 0.003 between *A.insignis* and *B.dubia*; Z = − 2.992, p-value = 0.001 between *A.insignis* and *Eublaberus sp.* and Z = − 0.039, p-value = 0.484 between *B.dubia* and *Eublaberus sp.* Considering the larger size of the Madagascar flat hissing cockroach, the difference

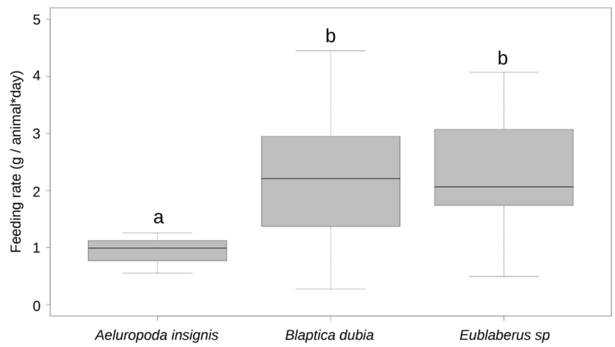


Fig. 6 Boxplots of the consumption rate *per animal per day* in the three cockroach species studied. The median or second quartile (Q_2, thick horizontal line), the standard deviation (outside each box) and the range of each variable (ends of the segments) are represented. Lowercase letters show significant differences from Dunn's nonparametric *post-hoc* test

is even more remarkable. Again the functional similarity between *B.dubia* and *Eublaberus sp.* in terms of organic waste recycling is demonstrated. In fact, the consumption of *B. dubia* and *Eublaberus sp.* is not only similar between them, but double that of *A. insignis* (Fig. 6). These consumption data have an impact on the daily production of blatticompost *per animal*, which is higher in *B. dubia* and lower in *A. insignis* (Fig. 7). Dunn's test showed significant differences between *A.insignis* and *B.dubia* (Z = − 2.843, p-value = 0.002) and between *A.insignis* and *Eublaberus sp.* (Z = − 3.093, p-value = 0.001), but not between *B.dubia* and *Eublaberus sp.* (Z = − 0.033, p-value = 0.487). In other words, it can be seen again that the response of the two smaller species is similar and that *Eublaberus sp.* shows an intermediate situation in consumption and blatticompost production. Again, there were no differences in blatticompost production for both diet groups within each species.

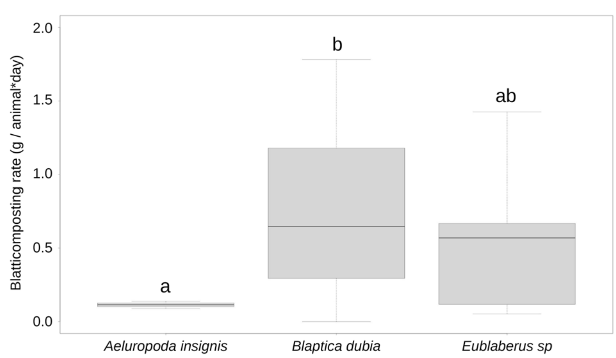


Fig. 7 Boxplots of blatticompost production per animal per day in the three cockroach species studied. The median or second quartile (Q_2, thick horizontal line), the standard deviation (outside each box) and the range of the variable (end of the segments) are represented. Lowercase letters show significant differences from Dunn's nonparametric *post-hoc* test

Wilcoxon test results were W = 12, p-value = 0.662 for *A.insignis*; W = 40.5, p-value = 0.496 for *B.dubia* and W = 146.5, p-value = 0.471 for *Eublaberus sp.*

In order to understand the overall potential of cockroaches on food waste recycling, blatticompost generation and savings in GHG emissions, results of *A. insignis*, *B. dubia* and *Eublaberus sp.* were pooled and expressed on an industrial scale. According to this, an industrial cockroach farm could consume 1015.9 g of organic residues *per* m^2 *per day*. This is equivalent to 304.8 mt/month*ha of food waste recycling (Fig. 8). Since blatticompost generation (in percentages of matter consumed) is similar between *A. insignis* (29%), *B. dubia* (23%) and *Eublaberus sp.* (28%) can be assumed an average composting rate of 26.7% of matter ingested for the three cockroach species. This implies a blatticompost production of 81.4 mt/month*ha. This blatticompost production would generate a gross income of 20,345.4 €/month*ha. In addition, one hectare under blatticomposting would be able to process the organic waste generated by 429,253.5 people. If the GHG emissions for each type of waste are taken into account, it follows a GHG emission saving of 817.2 mt/month*ha (Fig. 9).

Some chemical parameters of the blatticompost show slight differences between species (Table 4). In this regard, although the pH is close to neutral in all three roaches, *Eublaberus sp.* shows significant differences with a slightly more acidic pH. On the other hand, TOM, CEC and C contents are slightly lower in *A.insignis*. Phosphorus contents are slightly higher in *B. dubia* while potassium values are higher in *Eublaberus sp*. However, there are no differences between species in N contents, C/N ratio, B, Cu, Zn or Ni levels.

Discussion

The three species investigated were chosen because they are commonly bred by blatticulture hobbyists in Spain and are therefore readily available from specialized dealers. In addition, none of the three cockroaches is considered invasive anywhere in the world. On the other hand, they are functionally very different species in their social behavior, trophic habits, reproduction, growth, size, etc. Therefore, can be explored how these biological differences affect food waste recycling and choose not only the suitable species but also what functional characteristics should be looked for in other cockroaches to be studied in the future. It is also very important to consider how these biological differences between species affect us when extrapolating this study to an industrial scale. However, it is necessary to keep in mind that cockroaches can give very different results of consumption, growth and

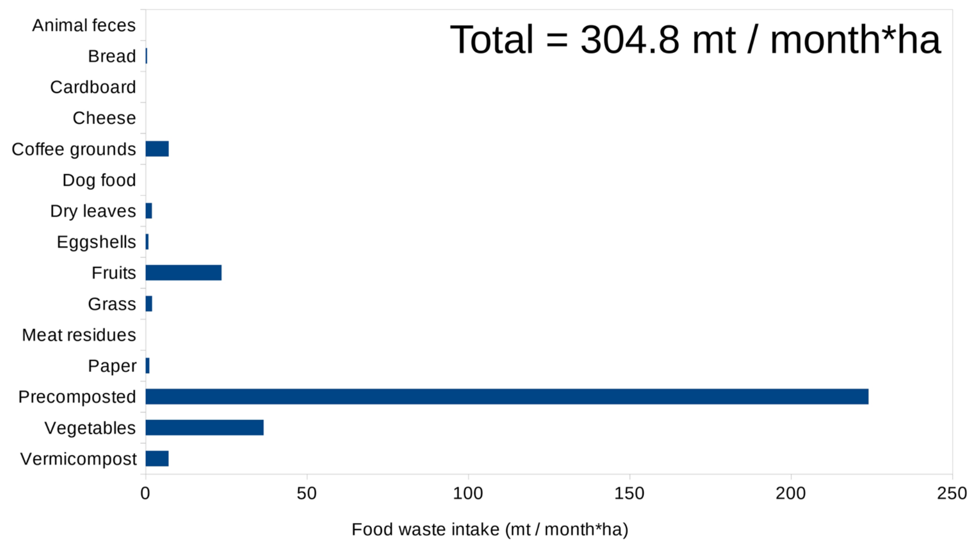


Fig. 8 Total amount of food processed monthly *per hectare* for the three cockroach species as a whole

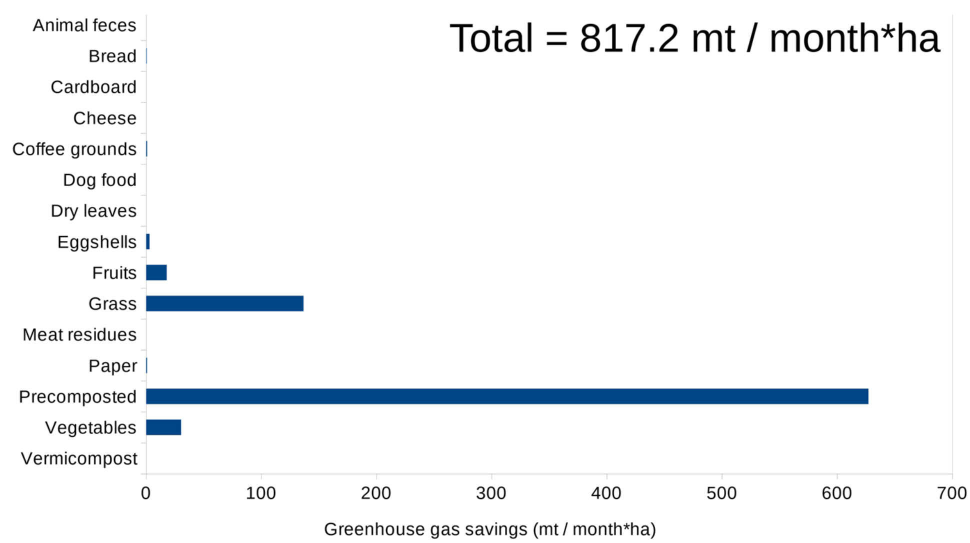


Fig. 9 Savings in CO_2 emissions over the study period transferred to industrial scale

Table 4 Chemical composition of the blatticompost of the three cockroach species studied. Letters correspond to significant differences in Dunn's nonparametric *post-hoc* test. Variables without letters show no significant differences between groups

Chemical parameter	*Aeluropoda insignis*	*Blaptica dubia*	*Eublaberus sp*
Carbon/Nitrogen ratio	10.63 ± 2.41	10.82 ± 1.51	10.86 ± 2.72
Total organic matter (%)	62.22 ± 3.30[a]	71.74 ± 5.08[b]	71.50 ± 3.09[b]
pH	7.29 ± 0.53[a]	7.23 ± 0.22[a]	6.78 ± 0.16[b]
Cationic exchange capacity (CEC, mS/cm)	4.47 ± 1.66[a]	6.14 ± 1.66[b]	5.13 ± 0.24[ab]
K (%)	1.47 ± 0.33[a]	1.86 ± 0.44[b]	2.06 ± 0.27[b]
K_2O (%)	1.77 ± 0.40[a]	2.24 ± 0.52[b]	2.48 ± 0.32[b]
Mg (%)	0.42 ± 0.11	0.48 ± 0.15	0.52 ± 0.24
MgO (%)	0.70 ± 0.18	0.80 ± 0.26	0.86 ± 0.40
P (%)	0.46 ± 0.02[ab]	0.51 ± 0.10[b]	0.43 ± 0.03[a]
P_2O_5 (%)	1.05 ± 0.06[ab]	1.16 ± 0.22[b]	0.97 ± 0.08[a]
C (%)	31.98 ± 2.51[a]	36.51 ± 2.07[b]	36.88 ± 0.51[b]
N (%)	3.13 ± 0.60	3.42 ± 0.35	3.57 ± 0.85
B (mg/kg)	53.84 ± 12.61	63.51 ± 16.85	53.04 ± 12.83
Zn (mg/kg)	92.19 ± 18.00	84.94 ± 13.69	79.23 ± 7.85
Cu (mg/kg)	30.60 ± 14.81	28.50 ± 4.19	28.90 ± 5.26
Ni (mg/kg)	5.23 ± 1.47[a]	4.67 ± 1.64[a]	9.18 ± 2.61[b]

reproduction according to very different environmental factors. Therefore, the comparisons given by us may differ from those of other authors if there are microclimatic, management or feeding variations. In this regard, although a detailed analysis of the growth and reproduction of the three species has not been elaborated, it is important to mention the observations made under the experimental conditions of this work. For example, *A. insignis* is an extremely prolific species, very well adapted to captivity, large in size and with marked sexual dimorphism [40]. Their nymphs are born very small (for the size of the adult) and take time to acquire a certain size. Therefore, achieving a functional colony of this species with a few specimens will take at least a year. Once obtained, it will be perfectly maintained if it does not reach an excessive density of adult males that will have to be separated to avoid stress to the rest of the colony.. There is very little scientific information published on this species, but it is known that its peculiar morphology responds to a very particular habitat: the rocky fissures in the center of the island of Madagascar (Cockroach Study Group: https://www.facebook.com/groups/blattodea). These central areas of the island are high plateaus at an altitude of over 800 m with a tropical climate (~ 1200 mm/m^2 *per year*) with two distinct seasons: one hot and humid (27–32 °C) and the other cold and dry (18–22 °C). This habitat explains the main characteristic of the species, which is its adaptability to different thermal and humidity environments. In fact, a reproduction at 20 °C has been observed in the laboratory, which is unusual for a tropical insect species of this size. However, the main problem with this species is that it is difficult to handle in terrariums, because although it has no wings and moves very slowly, it can climb any smooth surface. Also, this species does not tolerate well overcrowding, which compromises its exploitation on an industrial scale. It is necessary to maintain a suitable sex ratio, which would need to be studied in further work. This species have a cooperative care of adult females over their nymphs, which favors their survival, but hinders the reintroduction of females for the next reproduction. However, this behavior does not last as long as in *B.dubia* and lasts a few days. In addition, this species is not prone to eat meat scraps and as its rates of consumption and production of blatticompost are lower than in the two other studied cockroaches. Therefore, *A. insignis* is not a good option for recycling organic waste on an industrial scale.

The second studied species, the Argentine cockroach (*B. dubia*) lives in nature on leaf litter substrates in the tropical forests of northern South America. In this habitat, there is high humidity, high temperature and intense predation, which explains the high reproductive rates of this species and the fact that its nymphs hatch larger and develop earlier than other species. The species tolerates overcrowding excellently and it is common practice for breeders to maintain a ratio of five females to one male, as well as to separate the nymphs to facilitate a new reproduction. However, if the objective is to recycle food waste, these practices are not necessary, as the colony will renew itself without problems. Maintaining a functional colony from a few specimens could take half a year. In order to be able to move in this natural environment, *B.dubia* has a soft integument with little chitin and, therefore, its protein content is higher than that of other species [41]. Therefore, this cockroach is ideal for feeding reptiles and other exotic insectivores, as well as for the industrial production of protein meals [42]. In contrast, humidity could be a problem, since the nymphs dehydrate easily by its softer integument than adults. As it does not climb or fly, this species is ideal for large-scale management. In addition, it is the species that best withstands overcrowding of those studied in this work. Although it is more prolific than the other two species, the incubation and growth time of its nymphs is longer. Also, the nymphs are cared for by the adult females of the colony for at least one month. One of the advantages of this species is that it does not require substrate (like *Eublaberus sp.*), which greatly simplifies industrial rearing in big plastic boxes. In summary, due to the higher humidity and temperature requirements of this species, it does not seem to be the best choice for the dry weather of southwestern Spain. Only in facilities with isolation and very controlled microenvironment the species would give its potential and in these conditions it would be the best option of those tested.

Eublaberus sp. has already been studied as a species suitable for blatticompost production in previous studies [14]. Although it is a little known and widespread species among entomology enthusiasts, it is perfect for captive breeding. In this sense, it tolerates humidity ranges from 30 to 80%, although it prefers lower humidities than the other two species studied. Its thermal requirements are also very broad, since it breeds at 20 °C and tolerates temperatures of almost 40 °C if water is available. Its slow movements and the fact that it does not climb on smooth surfaces, nor can it fly (although it can glide from a high point) from the substrate make it ideal for large-scale management. In this sense, in breeding terrariums, densities of up to 8000 specimens per m^2 without them escaping have been managed. The voracity and resistance to overcrowding of this species are proverbial and at the aforementioned densities these cockroaches are capable of consuming a large volume of food. In fact, daily feeding seems to stimulate reproduction, which is not as seasonal as in other cockroach species. This corresponds to a very thermally stable habitat such as the bat caves where it lives in the wild. This non-seasonality in reproduction is undoubtedly a strong advantage for its industrial use. In addition, *Eublaberus sp.* nymphs grow faster than those of the other two species and this species does not appear to have cooperative care so there is no need to waste time separating nymphs to ensure the next breeding. These characteristics explain a curious paradox with this cockroach and that, although it is not as prolific as the other two, it is much easier to reach large colonies over time. Again, this is undoubtedly an appropriate strategy in the bat caves where they live in nature, where space is limited. *Eublaberus sp.* needs at least 15 cm of substrate, as the nymphs are diggers. This could be a problem for industrial rearing in stacked boxes, as these will acquire some weight. In fact, the 80×60x32 cm boxes used in this work became very heavy when they were full of blatticompost. This forced us to extract the fertilizer twice a week, which on an industrial scale would increase labor costs. Plastic boxes of 60×40x32 are perfect. This forces us to handle more boxes but in a much easier way. A great advantage of this species is the different trophic behavior between nymphs and adults. Nymphs are diggers, but adults usually occupy spaces above the substrate. This makes it possible to maintain an ideal spatial distribution in the breeding boxes and to increase the density and therefore the consumption of food waste. In addition, the fact that the nymphs are burrowers causes the substrate to be stirred and oxygenated, ensuring proper maturation.

In *Eublaberus sp.* there is hardly any sexual dimorphism. In fact, it is necessary to observe the abdomen (which requires trapping the specimen), but the maintenance of a certain male/female ratio is not important in this species, since nymphs become independent as soon as they are born and the females are therefore free to reproduce again. Also, unlike *A. insignis*, males do not fight each other, so there is no stress in the colony due to overcrowding. Some studies on a related species, *Eublaberus distanti*, indicate that above 4000 specimens *per* m^2 the nymphs develop more slowly [43]. However, as mentioned above a slow nymph development in *Eublaberus sp.* Ivory, even at densities of 8000 specimens/m^2 have not been observed. Species of the genus *Eublaberus* are very similar to each other so it is possible to speculate that diet type may have something to do here. Cave-dwelling cockroaches are adapted to high protein diets if the bats are insectivorous and to a high fiber diet if the bats are frugivorous. Despite this *Eublaberus sp.* Ivory is more generalist than other species of the genus and the nymphs have specialized in consuming more protein than adults. This phenomenon has been observed in other cockroach species [44]. Undoubtedly, *Eublaberus sp.* is the species that tolerates the highest protein content in its diet of the three species studied. All the characteristics of this species make it suitable for the recycling of organic wastes.

A large number of insect breeders have been keeping these three species (especially *B.dubia*) for decades and no biological invasion has been observed in the geographical area of experimentation (Mediterranean climate of SW Spain). In this sense, *A.insignis* dies in a few days if they escape from the rearing boxes where humidity and temperature are controlled. This is also the case of *B.dubia* which, in addition, has a much thinner exoskeleton, being more prone to dehydration. The habitat of *Eublaberus sp.* is so particular that it is not foreseeable that it will adapt to colonize other environments. However, if industrial breeding for waste recycling of any of these three species is proposed, it would be necessary to study their survival in experimental conditions with different humidity and temperature conditions. The fact that there are no invasive processes with these species anywhere in the world supports their suitability for industrial blatticulture.

Based on the experiences of keeping the three species, can be concluded that the feeding of cockroaches can be much more varied than that of other invertebrates used in composting such as isopods, millipedes, crickets or earthworms [45]. They even have advantages over the black soldier fly, as they can feed on hard materials such as cartilage, sawdust or seeds. When these cockroaches have nothing else to eat they gnaw on such non-nutritious materials as paper napkins, cardboard or mango pits. In the study area (southwestern Spain), it is only necessary to raise the indoor temperature a few degrees during a few days in winter to have a sustained activity of waste consumption throughout the year. However, outdoor rearing seems to us unfeasible even in areas with mild winters, since the thermal requirements of insects are higher than those of earthworms [29]. Consequently, the most advisable species for its lower thermal requirements is again *Eublaberus sp.* [14].

One of the main advantages of the use of any of the three cockroach species studied is their tendency to aggregate in high-density populations and in 3D spaces. This allows large numbers of animals to be maintained in small spaces and significantly increases food waste consumption *per* surface area. In contrast, most earthworms used in vermicomposting live in the first 15 cm of substrate, which greatly limits its efficiency. Only a few earthworm species support management in bins or stacked trays. In contrast, spatial utilization with *Eublaberus sp.* is ideal because the nymphs are burrowers and the adults are preferably located in 3D spaces on the substrate. A further adaptation to their natural habitat: bat caves where space is limited. The other two species are not burrowers, but the placement of lightweight 3D structures greatly multiplies the density of animals. However, a digging species seems more interesting in food waste recycling because it contributes to aerate the substrate. In this regard, an excessive guano hydration has been detected in the other two non-digging species, especially in *A. insignis*.

The W–L curves of these species are the first time they have been calculated. This is a very useful and simple method to determine the effect of different types of diet in future studies. In this way, could be a methodology to assess the suitability of these cockroach species in the recycling of wastes that are very difficult to degrade, such as those from the olive industry, slaughterhouses, etc. In this sense, recent research analyzed the consumption of the invasive toxic algae species *Rugulopteryx okamurae* by *Eublaberus sp.* Ivory and other invertebrate species over a period of 5 weeks and did not observe significant decreases in weight, although they did observe decreases in consumption [14]. Although cockroaches can accumulate reserves in special cells in their abdomen [29], it is necessary to determine the effect of this type of residues in the longer term. It is in these contexts that W–L curves are particularly useful. Although, the three species studied do not differ significantly in their W–L curves, we should explore whether this occurs in other species in future research. Although there is a consensus in the blatticulture forums in recognizing the voracity of *Eublaberus sp.* it is no less true that most cockroach species have not been tested until now in bioremediation of organic wastes.

Regarding the K_{rel} parameter, *B.dubia* shows the highest values being on average 1.0, somewhat higher than in *Eublaberus sp.* although these differences are not significant. On the contrary, the peculiar morphology of *A.insignis* makes this species present significant differences with respect to the other two. However, this should not affect the industrial use of this species. The three species present very high growth rates and the time needed to have functional colonies could be shorter in *A.insignis* than in the other two species, but its resistance to overcrowding is lower as mentioned above.

Concerning waste consumption rates, it seems that the three species studied show very similar voracities to those obtained with BSFL composting [52]. However, comparative studies under the same experimental conditions of microclimate and feeding are necessary to compare both groups of species.

The combined average production of blatticompost of the three species is 1.02 kg/m^2*day and it is clear that this value is far from the compost production generated by other systems such as vermicomposting [46] or composting with free-living microorganisms in its different variants [47]. However, at the level of food waste consumption, cockroaches are much more efficient. This apparent contradiction occurs because cockroaches, although extremely voracious, use food energy prioritizing growth and reproduction [29]. This is an advantage if the main objective is the recycling of food waste and not the generation of fertilizers. However, they are capable of easily transforming organic waste that is difficult for earthworms, such as citrus peels, cooking oils, meat waste or toxic marine macroalgae such as *Rugulopteryx okamurae*, an invasive species that generates a large amount of biomass, whose composting with *Eublaberus sp.* has already been experimented in a previous work [14]. In this sense, cockroaches are highly profitable if the alternative to this food waste is landfilling with the collateral effects of time and odors that this entails [47]. Moreover, the profitability of using cockroaches in food waste recycling increases with the chemical and biological quality of their blatticompost, whose parameters, although not complete, can be evaluated as quality indicators according to European recommendations [48]. In addition, blatticompost is very attractive to the consumer because of its very dark color and "forest" smell. This has been confirmed by many people who have approached the laboratory and after their initial mistrust, try it on their plants and ask for more.

Also, the freshly extracted blatticompost from the terrariums has a moisture value that allows it to be sieved with 4 mm mesh. By storing it in holed buckets for a few weeks, the blatticompost loses enough moisture to allow it to be re-sieved with 2 mm meshes to separate out the smaller nymphs. This is problematic with *Eublaberus sp.* as even the smallest nymphs bury themselves deeply. Since the average organic matter content of freshly extracted blatticompost is slightly high ($68.51 \pm 6.99\%$), a two-week maturation period is mandatory. During this rest, the temperature increases slightly due to the consumption by microorganisms of the undigested residual organic matter. Undoubtedly, blatticompost is much easier to process than vermicompost and this is a time saving and an advantage to consider this activity at industrial level. Of the three species studied, *B. dubia* produces slightly more blatticompost than *Eublaberus sp.* but the differences are not significant. If it is taken into account that in *Eublaberus sp.* the nymphs are diggers and the blatticompost is therefore more aerated, there is a new argument to recommend this species among the three tested.

In the analysis of the profitability of the use of cockroaches in food waste recycling, it is necessary to consider the excellent chemical quality of their blatticompost according to European recommendations (http://compostnetwork.info). In this sense, the C/N ratio does not show differences between species being the joint average value of 10.76 ± 2.15 slightly low but acceptable. Also the N contents are similar in the three species and on average their value is 3.36 ± 0.6, i.e. slightly higher than what is shown by most studies on vermicompost [47]. This forces the use of blatticompost at lower rates than vermicompost, which is highly interesting. That is, if cockroaches compost 26.7% of the ingested material, this is just over half the average composting rate of earthworms (~45%). If, in addition, their N content is slightly less than twice that of earthworms, cockroaches are ultimately more profitable as composters. Therefore, blatticompost is more concentrated than other types of compost with consequent savings in storage, transport and use but with similar results. In this sense, new studies are needed to see the viability of blatticompost in different doses and crops. Potassium contents are also slightly higher than in the case of vermicompost, but the same is not true for phosphorus. Consequently, blatticompost has a really very interesting nutritive value similar to that of other organic fertilizers from insects [52]. The possible deficiencies observed are more the effect of the type of feeding used in this work than the effect of the cockroaches and could be improved by some techniques such as the incorporation of biochar or co-composting [53, 54]. In the case of pH, the average values of 7.15 ± 0.4 are appropriate. In *Eublaberus sp.* they are somewhat lower than in the other species which is very convenient, since a slightly acidic pH favors the uptake of micronutrients [49]. Most studies on vermicompost [47, 55] or black soldier fly larvae (BSFL) composting [52] composition indicate a higher pH [47] with which blatticompost would be even better. However, the values of the cation exchange capacity (CEC) of blatticompost are slightly higher (on average 5.36 ± 1.66 ms/cm) than those established in the European regulations (should not exceed 4 ms/cm). This may be due to the fact that the studied cockroaches have also been fed with cooked residues that present high contents of mineral salts [50]. With a feed without these components the CEC values would be even better. This explanation is supported by the fact that only the blatticompost of *A. insignis* meets the CEC standards. It is precisely the most frugivorous of the three species and tends to show less preference for cooked food. Another possible explanation for the slightly elevated CEC values is that cockroaches have a particular and unique metabolism among insects as they store N in the form of urea [29]. However, this slightly elevated CEC value, related to salt content, would not be problematic in clay soils such as those found in much of the geographical area where this study was conducted [51]. Regarding metal contents, blatticompost is perfectly usable. In this regard, it is advisable to promote research to determine the capacity of cockroaches to accumulate heavy metals, as they have already demonstrated their efficiency in some bioremediation studies [14]. Among the metals, nickel is the only one that appears in a different concentration in *Eublaberus sp.* compared to the other two species. Recent studies indicate that there are insects that accumulate large amounts of nickel in their organism, especially in the gut (~75%), Malpighian tubules and exuviae [56]. These are exclusively phytophagous insects that feed on plants with hyperaccumulation of nickel. It has been proposed that this would constitute a defensive mechanism against predators [56]. The fact that the blatticompost of *Eublaberus sp.* has more nickel indicates that it accumulates less nickel in its body and would be consistent with it being the least phytophagous species. In fact, we have mentioned that in nature it lives in bat caves and feeds on their carcasses and droppings. The other two species live in forests and are mainly phytophagous. On the other hand, due to the habitat of *Eublaberus sp.* it has no natural predators. Its population levels are regulated by intraspecific competition and inhibition of reproduction [14]. Finally, *Eublaberus sp.* eats its own exoskeletons, so accumulating nickel in them would be pointless. The consequences as applied to industry are obvious. If we wanted to make blatticompost with nickel-rich remains we should use *Blaptica dubia* and otherwise any of the other species. With a high content of meat remains, the indicated species would be *Eublaberus sp.*

Finally, it is necessary to mention that one of the main advantages of blatticomposting is that it does not generate leachates or bad odors. In fact, the smell of blatticompost is reminiscent of a humus-laden forest floor. As has been previously mentioned, it is enough to sieve the blatticompost to obtain an excellent compost. The microbiology of blatticompost has not been analyzed in this work, since it would require a specific study of this aspect alone. However, previous studies on the intestinal microbiota of these insects show that they contain antimicrobial peptides [29]. Undoubtedly, this is a defensive strategy against a diet based on decomposing material. This factor, together with the fact that they are fed with domestic waste from the same day, could give microbiological values with absence of pathogens, although specific studies on this aspect are necessary.

A strong argument for the adoption of blatticomposting as an organic waste treatment system is the enormous saving in greenhouse gas emissions. This saving has been calculated assuming average emissions of organic waste from various scientific publications, but not directly measured. However, it is reasonable to assume that the extreme voracity of composting cockroaches combined with the fact that they eat the material directly and not when it starts to decompose (as earthworms do) should always produce fewer emissions than vermiculture. Most probably the level of emissions from blatticomposting should be similar to that produced by BSFL composting, since in both cases the insects feed by gnawing the material and not by suction. All this will require a specific study, the complexity of which must be addressed in further work.

Results undoubtedly show the enormous potential of cockroaches as broad-spectrum organic waste bioconverters. This allows us not only to reduce organic waste and avoid its collateral effects on environmental health and GHG emissions, but also to reduce costs in the production of organic fertilizers whose demand is increasing. Currently, blatticompost is used only in laboratories or by certain insect breeding enthusiasts. There is no evidence so far of its use on a large scale anywhere on the planet. The bad image of cockroaches, associated with the unhealthiness of decomposing material, should not distract us from seeing them scientifically for what they are: decomposing insects with enormous potential as bioconverters and which have been perfecting this function by evolution since the distant Carboniferous era. Hopefully, this work will stimulate further research on more species, their functional role and the characteristics of the blatticompost obtained. This is a powerful tool to solve the problem of organic waste worldwide.

Conclusions

Humanity is facing a serious problem with organic waste, as its production is constantly increasing. Many solutions have been proposed, such as incineration, pyrolysis or composting. Within this last option, techniques with free-living microorganisms are mostly used by means of static piles, mobile piles, passive aeration, pit, Takakura system, Bokashi, etc. The disadvantages of these methods are the generation of odors, the non-elimination of heavy metals, the production of leachates or a slight emission of greenhouse gases (GHG) in the initial stages of the process. Another technique widely used in the treatment of organic waste is vermicomposting, which is much more advisable due to its lower GHG emissions and higher quality compost. In contrast to these techniques, the use of composting cockroaches (blatticomposting) for the recycling of organic waste has been proposed. Results show that they are highly voracious and give a compost (blatticompost) of superior quality even to vermicompost. GHG emissions are practically zero, since these animals are very voracious and do not need the waste to be partially degraded like earthworms. In this work, are compared three species widely used in agriculture and is proposed the ivory cockroach (*Eublaberus sp.*) as the ideal species for use on an industrial scale.

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Author Contributions In order of signature, the authors' contributions were as follows: DP carried out the analyses of cockroach consumption in the laboratory, the statistical treatment of the data and was involved in the bibliographic review and writing of the manuscript. JCGG is the coordinator of the working group that was in charge of finding the necessary resources, reviewing the bibliography and writing and correcting the manuscript.

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Data availability The data that allowed this work to be carried out will be available to the scientific community after publication and on the basis of justified arguments for further studies.

Declarations

Conflict of interest None of the authors are in charge of companies, nor do they work in politics. We are researchers committed to the environment and the need to provide solutions to the problems of waste generated by invasive algal blooms. Our commitment is exclusively to science.

References

1. Kaza, S., Yao, L.C., Bhada-Tata, P., Van Woerden, F.: What a waste 2.0. A global snapshot of solid waste management to 2050. Urban Development, World Bank, Washington (2018). https://openknowledge.worldbank.org/handle/10986/30317
2. Fowles, T.M., Nansen, C., Närvänen, E., Mesiranta, N., Mattila, M., Heikkinen, A.: Insect-based bioconversion: value from food waste. In: Närvänen, E., Mesiranta, N., Mattila, M., Heikkinen, A. (eds.) Food waste management: solving the wicked problem, pp. 321–346. Palgrave Macmillan, Cham (2020). https://doi.org/10.1007/978-3-030-20561-4_12.
3. Amicarelli, V., Lagioia, G., Bux, C.: Global warming potential of food waste through the life cycle assessment: an analytical review. Environ. Impact Assess. Rev. **91**, 106677 (2021). https://doi.org/10.1016/j.eiar.2021.106677
4. Kavitha, S., Kannah, R.Y., Kumar, G.,Gunasekaran, M., Banu, J.R.: Introduction: sources and characterization of food waste and food industry wastes. In: Banu, R., Kumar, G., Gunasekaran, M., Kavitha, S. (eds.) Food waste to valuable resources, pp. 1–13. Academic Press, Cambridge (2020). https://doi.org/10.1016/B978-0-12-818353-3.00021-3
5. Poore, J., Nemecek, T.: Reducing food's environmental impacts through producers and consumers. Science **360**(6392), 987–992 (2018). https://doi.org/10.1126/science.aaq0216
6. Brunner, P.H., Fellner, J.: Setting priorities for waste management strategies in developing countries. Waste Manage. Res. **25**(3), 234–240 (2007). https://doi.org/10.1177/2F0734242X07078296
7. Thi, N.B.D., Kumar, G., Lin, C.Y.: An overview of food waste management in developing countries: current status and future perspective. J. Environ. Manage. **157**, 220–229 (2015). https://doi.org/10.1016/j.jenvman.2015.04.022
8. Borges, M.M., da Costa, D.V., Trombete, F.M., Câmara, A.K.F.I.: Edible insects as a sustainable alternative to food products: an insight into quality aspects of reformulated bakery and meat products. Curr. Opin. Food Sci. **46**, 100864 (2022). https://doi.org/10.1016/j.cofs.2022.100864
9. Xie, Y.T., Ma, Y.F., Cai, L.L., Jiang, S., Li, C.B.: Reconsidering meat intake and human health: a review of current research. Mol. Nutr. Food Res. **66**(9), 2101066 (2022). https://doi.org/10.1002/mnfr.202101066

10. Parfitt, J., Barthel, M., Macnaughton, S.: Food waste within food supply chains: quantification and potential for change to 2050. Philos. Trans. R. Soc. London, Ser. B. 365(1554), 3065–3081 (2010). https://doi.org/10.1098/rstb.2010.0126.
11. Bernstad, A., La Cour, J.: Review of comparative LCAs of food waste management systems. Current status and potential improvements. Waste Manage. **32**, 2439–2455 (2012). https://doi.org/10.1016/j.wasman.2012.07.023
12. Vermeulen, S.J., Campbell, B.M., Ingram, J.S.I.: Climate change and food systems. Annu. Rev. Environ. Resour. **37**, 195–222 (2012). https://doi.org/10.1146/annurev-environ-020411-130608
13. Dmuchowski, W., Baczewska-Dąbrowska, A.H., Gworek, B.: Agronomy in the temperate zone and threats or mitigation from climate change: a review. Catena **212**, 106089 (2022). https://doi.org/10.1016/j.catena.2022.106089
14. Patón, D., García-Gómez, J.C., Loring, J., Torres, A.: Composting the invasive toxic seaweed *Rugulopteryx okamurae* using five invertebrate species, and a mini-review on composting macroalgae. Waste Biomass Valoriz. (2022). https://doi.org/10.1007/s12649-022-01849-z
15. Oonincx, D.G.A.B., Van Itterbeeck, J., Heetkamp, M.J.W., Van den Brand, H., Van Loon, J.J.A., Van Huis, A.: An exploration on greenhouse gas and ammonia production by insect species suitable for animal or human consumption. Plos One **5**(12), e14445 (2010). https://doi.org/10.1371/journal.pone.0014445
16. Franco, A., Scieuzo, C., Salvia, R., Petrone, A.M., Tafi, E., Moretta, A., Schmitt, E., Falabella, P.: Lipids from *Hermetia illucens*, an innovative and sustainable source. Sustainability **13**(18), 10198 (2021). https://doi.org/10.3390/su131810198
17. Sangiorgio, P., Verardi, A., Dimatteo, S., Spagnoletta, A., Moliterni, S., Errico, S.: *Tenebrio molitor* in the circular economy: a novel approach for plastic valorisation and PHA biological recovery. Environ. Sci. Pollut. Res. **28**(38), 52689–52701 (2021). https://doi.org/10.1007/s11356-021-15944-6
18. Ruschioni, S., Loreto, N., Foligni, R., Mannozzi, C., Raffaelli, N., Zamporlini, F., Pasquini, M., Roncolini, A., Cardinali, F., Osimani, A., Aquilanti, L., Isidoro, N., Riolo, P., Mozzon, M.: Addition of olive pomace to feeding substrate affects growth performance and nutritional value of mealworm (*Tenebrio molitor* L.) larvae. Foods 9(3), 317 (2020)
19. Sangiorgio, P., Verardi, A., Dimatteo, S., Spagnoletta, A., Moliterni, S., Errico, S.: Valorisation of agri-food waste and mealworms rearing residues for improving the sustainability of *Tenebrio molitor* industrial production. J. Insects Food Feed **8**(5), 509–524 (2022). https://doi.org/10.3920/JIFF2021.0101
20. Riekkinen, K., Väkeväinen, K., Korhonen, J.: The effect of substrate on the nutrient content and fatty acid composition of edible insects. Insects **13**, 590 (2022). https://doi.org/10.3390/insects13070590
21. Petrescu-Mag, R., Rastegari, H., Petrescu, D.: Consumers' acceptance of the first novel insect food approved in the European Union: predictors of yellow mealworm chips consumption. Food Sci. Nutr. (2022). https://doi.org/10.1002/fsn3.2716
22. Awal, R., Rahman, M., Choudhury, A.R., Hasan, M., Rahman, T., Mondal, F.: Influences of artificial light on mating of black soldier fly (*Hermetia illucens*). A review. Int. J. Trop. Insect Sci (2022). https://doi.org/10.1007/s42690-022-00786-7
23. Gligorescu, A., Fischer, C.H., Larsen, P.F., Norgaard, J.V., Heckman, L.H.L.: Production and optimization of *Hermetia illucens* (L.) larvae reared on food waste and utilized as feed ingredient. Sustainability **12**(23), 9864 (2022). https://doi.org/10.3390/su12239864
24. Lundy, M.E., Parrella, M.P.: Crickets are not a free lunch: protein capture from scalable organic side-streams via high-density populations of *Acheta domesticus*. Plos One **10**(4), e0118785 (2015). https://doi.org/10.1371/journal.pone.0118785
25. Quek, X.T., Liang, L., Tham, H.H., Yeo, H., Tan, M.K., Tan, H.T.W.: Are the growth and survival of *Acheta domesticus* comparable when reared on okara, waste vegetables and premium animal feed?. J. Insects Food Feed **6**(2), 161–168 (2019). https://doi.org/10.3920/JIFF2019.0039
26. Gutiérrez, Y., Fresch, M., Ott, D., Brockmeyer, J., Scherber, C.: Diet composition and social environment determine food consumption, phenotype and fecundity in an omnivorous insect. R. Soc. Open Sci. **7**, 200100 (2020). https://doi.org/10.1098/rsos.200100
27. Vaga, M., Berggren, Å., Jansson, A.: Growth, survival and development of house crickets (*Acheta domesticus*) fed flowering plants. J. Insects Food Feed **7**(2), 151–161 (2021). https://doi.org/10.3920/JIFF2020.0048151
28. Reilly, L.M., Hu, Y., Von Schaumburg, P.C., De Oliveira, M.R.D., He, F., Rodriguez-Zas, S.L., Southey, B.R., Parsons, C.M., Utterback, P., Lambrakis, L., Da Costa, D.V., Bertechini, A.G., Saad, F.M.O.B., De Godoy, M.R.C.: Chemical composition of selected insect meals and their effect on apparent total tract digestibility, fecal metabolites, and microbiota of adult cats fed insect-based retorted diets. J. Anim. Sci. **100**(2), 1–14 (2022). https://doi.org/10.1093/jas/skac024
29. Bell, W.J., Roth, L.M., Nalepa, C.A.: Cockroaches: ecology, behaviour and natural history. Johns Hopkins University Press, Baltimore (2007).
30. Lopes, S.M., Heeren de Oliveira, E., Khouri, A.: New species of *Eublaberus* Hebard, 1920, new records for the genus and description of the male of *E. variegatus* R. S. Albuquerque, 1972 (*Blaberidae, Blaberinae*). Biota Neotrop. **15**(2), 1–3 (2015). https://doi.org/10.1590/1676-06032015005113
31. Froese, R.: Cube law, condition factor and weight–length relationships: history, meta-analysis and recommendations. J. Appl. Ichthyol. **22**, 241–253 (2006). https://doi.org/10.1111/j.1439-0426.2006.00805.x
32. Stevenson, R.D., Woods, W.A., Jr.: Condition indices for conservation: new uses for evolving tools. Integr. Comp. Biol. **46**(6), 1169–1190 (2006). https://doi.org/10.1093/icb/icl052
33. Breusch, T.S., Pagan, A.R.: A simple test for heteroscedasticity and random coefficient variation. Econometrica **47**, 1287–1294 (1979). https://doi.org/10.2307/1911963
34. Kolassa, J.E.: An introduction to non-parametric statistics. Chapman and Hall/CRC, New York (2020). https://doi.org/10.1007/978-3-319-30634-6
35. Czudaj, S., Möllmann, C., Fock, H.O.: Length–weight relationships of 55 mesopelagic fishes from the eastern tropical North Atlantic: across- and within-species variation (body shape, growth stanza, condition factor). J. Fish Biol. **101**(1), 26–41 (2022). https://doi.org/10.1111/jfb.15068
36. Benjamini, Y., Yekutieli, D.: The control of the false discovery rate in multiple testing under dependency. Ann. Stat. **29**, 1165–1188 (2001). https://doi.org/10.1214/aos/1013699998
37. Clune, S.: Calculating GHG impacts of meals and menus using streamlined LCA data. In: Sabaté, J. (eds.), Environmental Nutrition, pp. 157–178. Academic Press, Cambridge (2019). https://doi.org/10.1016/B978-0-12-811660-9.00010-2.
38. Moult, J.A., Allan, S.R., Hewitt, C.N., Berners-Lee, M.: Greenhouse gas emissions of food waste disposal options for UK retailers. Food Policy **77**, 50–58 (2018). https://doi.org/10.1016/j.foodpol.2018.04.003
39. Scherhaufer, S., Moates, G., Hartikainen, H., Waldron, K., Obersteiner, G.: Environmental impacts of food waste in Europe. Waste Manage. **77**, 98–113 (2018). https://doi.org/10.1016/j.wasman.2018.04.038
40. Hunsinger, E., Root-Gutteridge, H., Cusano, D.A., Parks, S.E.: A description of defensive hiss types in the flat horned hissing

cockroach (*Aeluropoda insignis*). Bioacoustics **27**(3), 261–271 (2018). https://doi.org/10.1080/09524622.2017.1327371
41. Yi, L.Y., Lakemond, C.M.M., Sagis, L.M.C., Eisner-Schadler, V., van Huis, A., van Boekel, M.A.J.S.: Extraction and characterisation of protein fractions from five insect species. Food Chem. **141**(4), 3341–3348 (2013). https://doi.org/10.1016/j.foodchem.2013.05.115
42. Ardestani, M.M., Sustr, V., Hnilička, F., Frouz, J.: Food consumption of the cockroach species *Blaptica dubia* Serville (*Blattodea: Blaberidae*) using three leaf litter types in a microcosm design. Appl. Soil Ecol. **150**, 103460 (2020). https://doi.org/10.1016/j.apsoil.2019.103460
43. Rivault, C.: Influence du groupement sur le développement chez *Eublaberus distanti* (*Dictyoptere, Ins.*). Insectes Sociaux, Paris **30**(2), 210–220 (1983)
44. Adams, T., Pennings, S.C.: Dietary protein and sodium co-limit cockroach growth and reproduction. Ecol. Entomol. **47**(5), 831–841 (2022). https://doi.org/10.1111/een.13173
45. Cerreta, A.J., Smith, D.C., Heugten, K.A.V., Minter, L.J.: Comparative nutrient analysis of four species of cockroaches used as food for insectivores by life stage, species, and sex. Zoo Biol. **1**, 26–33 (2022). https://doi.org/10.1002/zoo.21647
46. Munroe, G.: Manual of on-farm vermicomposting and vermiculture. Org. Agric. Centre of Canada, Nova Scotia, Canada (2007).
47. Rynk, R., Black, G., Gilbert, J., Biala, J., Bonhotal, J., Schwarz, M., Cooperband, L.: The composting handbook. Academic Press, Cambridge (2022). https://doi.org/10.1016/C2019-0-05417-9
48. Estrella-Gonzalez, M.J., Suarez-Estrella, F., Jurado, M.M., Lopez, M.J., Lopez-Gonzalez, J.A., Siles-Castellano, A.B., Muñoz-Merida, A., Moreno, J.: Uncovering new indicators to predict stability, maturity and biodiversity of compost on an industrial scale. Bioresource Technol. **313**, 123557 (2020). https://doi.org/10.1016/j.biortech.2020.123557
49. Sathyanarayan, S.R., Warke, V.G., Mahajan, G.B., Annapure, U.S.: Soil free nutrient availability to plants. J. Plant Nut. **46**(5), 801–814 (2022). https://doi.org/10.1080/01904167.2022.2071736
50. Iqbal, M.K., Ahmed, K., Shafiq, T., Saeed, M.K.: Changes in biochemical characteristics of stability in food waste compost by four different techniques. ICME (International Conference on Complex Medical Engineering). (2009). https://doi.org/10.1109/ICCME.2009.4906601
51. Trueba, C., Millán, R., Schmid, T., Roquero, C., Magister, M. Base de datos de propiedades edafológicas de los suelos españoles III, Extremadura. Informes Técnicos CIEMAT, 858. Spain (1978).
52. Purkayastha, D., Sarkar, S.: Performance evaluation of black soldier fly larvae fed on human faeces, food waste and their mixture. J. Environ. Manag. **326**, 116727 (2023). https://doi.org/10.1016/j.jenvman.2022.116727
53. Balachandar, R., Karmegam, N., Awasthi, M.K., Chang, S.W., Selvi, P.K., Balachandar, R., Chinnappan, S., Azelee, N.I.W., Munuswamy-Ramanujam, G.: Valorization of food waste and poultry manure through co-composting amending saw dust, biochar and mineral salts for value-added compost production. Bioresource Technol. **346**, 126442 (2022). https://doi.org/10.1016/j.biortech.2021.126442
54. Balachandar, R., Awasthi, M.K., Karmegam, N., Chang, S.W., Chaudhary, D.K., Selvam, A., Nguyen, D.D., Milon, A.R., Munuswamy-Ramanujam, G.: Co-composting of food waste and swine manure augmenting biochar and salts: Nutrient dynamics, gaseous emissions and microbial activity. Bioresource Technol. **344**, 126300 (2022). https://doi.org/10.1016/j.biortech.2021.126300
55. Balachandar, R., Biruntha, M., Yuvaraj, A., Thangaraj, R., Subbaiya, S., Govarthanan, M., Kumar, P., Karmegam, N.: Earthworm intervened nutrient recovery and greener production of vermicompost from *Ipomoea staphylina*. An invasive weed with emerging environmental challenges. Chemosphere **263**, 128080 (2021). https://doi.org/10.1016/j.chemosphere.2020.128080
56. Boyd, R.S.: High-nickel insects and nickel hyperaccumulator plants: a review. Insect Sci. **16**, 19–31 (2009). https://doi.org/10.1111/j.1744-7917.2009.00250.x