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Black Soldier Fly *Hermetia illucens* (Diptera: Stratiomyidae) For Achieving Sustainable Development Through Circular Economy

Anita V. Sable [a*], Faria S. Khan [b] and Jayshri B. Tawale [c]

[a] Department of Entomology, College of Agriculture, Osmanabad, Maharashtra-413509, India.
[b] Department of Entomology, College of Agriculture, Parbhani, Maharashtra-431402, India.
[c] Department of Economics, College of Agriculture, Osmanabad, Maharashtra -413509, India.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

A circular economy is a strategy aimed at optimizing resources so that sustainability can be achieved. The world needs to shift from linear economy to circular economy. Black soldier fly *Hermetia illucens* l. (Diptera: Stratiomyidae) is gaining popularity in recent years for its tremendous capacity for organic waste management and bioconversion of organic waste into nutrient rich compost. Larvae and prepupae of black soldier fly have been used as feed for poultry birds, fishes, other animals and it can be used as nutrient rich food for humans. It is a promising source of protein and can be utilized for chitin, protein and grease extraction and biodiesel production. Due to its potential applicability at various industries and thereby recycling the organic waste and close the

**Corresponding author: E-mail: anitavsable@gmail.com;*

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loop in the production system, it has gained attention in recent years for achieving some of the sustainable development goals adopted by united nations by transition from linear to circular economy. India has vast potential for BSF-based industries.

Keywords: Black soldier fly; Hermetia illucens; waste management; animal feed; biodiesel; sustainable development; circular economy.

ABBREVIATIONS

BSF : Black Soldier Fly.
SDG : Sustainable Development Goal

1. INTRODUCTION

In 2015, the United Nations general assembly adopted the 17 sustainable development goals (SDGS), aiming to transition the world to a sustainable and resilient trajectory by 2030. [1]. By 2050, the global population is projected to reach 9.7 billion [2], presenting a significant challenge to food security. To meet the nutritional needs of this growing population, food production will need to increase by 70%, necessitating sustainable agricultural practices and innovative solutions to ensure global food security [3]. To address the pressing global issues of hunger, poverty, nutrition, and food security, a significant increase in food productivity is crucial. by 2050, the demand for cereals is expected to rise by approximately 50% for both food and feed purposes. Moreover, the demand for other essential food products like meat, dairy, fish, vegetable oils, and more is projected to grow at an even faster rate. [4,5,6]. To achieve a more sustainable food system, a gradual transition from a linear economy (characterized by a "make-take-waste" approach) to a circular economy (based on "reduce-reuse-recycle and recover" principles) is essential. Over the past decade, the concept of a circular economy has gained global significance, emerging as a vital theme worldwide. By embracing circular economy principles, we can foster sustainable and resource-efficient policies, leading to long-term benefits for both the environment and society [8]. “Further, the term circular bioeconomy was introduced by the European commission, which defines it as: “The production of renewable biological resources and the conversion of these resources and waste streams into value-added products such as food, feed, bio-based products, and bioenergy. Sustainability and circularity must be at the center of the bioeconomy if it is to be successful. These objectives will promote the renewal of our industry, the modernization of our primary production systems and the protection of the environment and will help enhance biodiversity” [9].

“Many species of insects are capable of converting biological wastes into valuable products like compost and also are the rich source of nutrients. insects reduce the above-mentioned societal challenges, create healthier and more sustainable food, and reduce animal feed production and consumption. Insects are rich in proteins (37–63%) and fats (20–40%), with well-balanced amino acid and fatty acid profiles and they are good sources of minerals and vitamins” [10]. “Insects have a high feed conversion rate, requiring much less feed to produce the same amount of animal proteins. most of the insects can be cultured on locally available industrial and agricultural waste streams, recycling a loss into a valuable protein source. households across all continents wasted over 1 billion meals a day in 2022, while 783 million people were affected by hunger and a third of humanity faced food insecurity” [11]. “Insects have great potential to convert these food waste into energy. insect biorefinery is a concept of using insect as a tool to convert biomass waste into energy and other beneficial products with concomitant remediation of the organic components. The exploitation of insects and their bioproducts have become more popular in recent years” [12]. “In near future, insect sector can become an important component of sustainable circular agriculture by closing nutrient and energy cycles, fostering food security, and minimising climate change and biodiversity loss, thereby contributing to sustainable development” [13,14].

“Black soldier fly *hermetia illucens* l. (diptera: stratiomyidae) is a nutritious feed component for livestock with high protein levels. Larvae and pupae rich in nutrients. they are known to convert organic waste into compost which is also rich in nutrients” [12,13,14]. Black soldier fly (bsf) can be reared on a wide variety of organic residues. therefore, the production of bsf within a circular agriculture is feasible and that can help in reducing the import of expensive feed components, such as fishmeal or soymeal for livestock production.

2. BIOLOGY AND DISTRIBUTION OF BSF

"BSF is wasp-like fly found in rural, urban and forest environments. It is native to the Neotropics, but now found in every zoogeographic region following decades of spread throughout the warmer parts of the world" [15]. "It is found on every continent except Antarctica. They are endemic to the tropical and warm temperate regions of the Western Hemisphere, dispersing to the continents on the Eastern Hemisphere by human interactions". [16,17]. "It is eurythermal species which can tolerate wide extremes of temperature. It consists of four life stages *viz*. egg, maggot, pupa and adult (Fig.1). Adult female lay eggs in cracks and crevices near food in a dry place. Eggs hatch in about more than 4 days at a temperature of 27-29°C to about 3.5 days at 30°C" [18]. "Maggot is white, translucent with reddish brown head. Larva passes through six instars. The larval body comprises 11 segments covered by hairs and bristles. The larvae consistently feed on organic waste and reduces it to compost. The mouthparts of the larval stage are very strong and are well adapted for feeding on waste matter. The last instar larva become greyish and does not feed. Larva moults into pupa in about 18 days. Pupa migrates towards the dry place away from the food substrate" [16]. "The life cycle last approximate 45 days [Egg (4 days), Larva (18 days), Pupa (14 days), and adult (9 days)]. The total life cycle of BSF completes about 45 days but may extend up to four months" [19] depending upon composition of food substrate, temperature, humidity etc.

3. BSF FOR ORGANIC WASTE MANAGEMENT AND COMPOST PRODUCTION

"Waste management is one of the most important challenges of the twenty-first century. Many aspects of societies, economies and the environment are influenced by this issue. Addressing this challenge also contributes towards the achievement of more than half of the SDGs especially those related to health, climate change, food security, poverty alleviation,

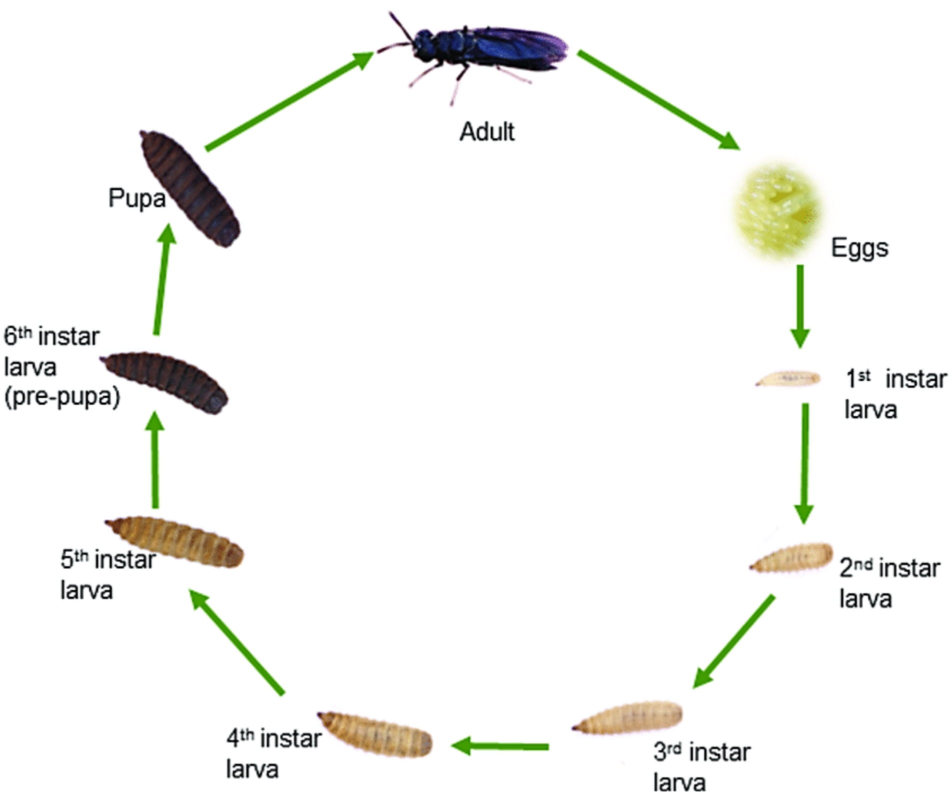

Fig. 1. Biology of black soldier fly [20]

responsible consumption and production" [21]. "This can be achieved through waste valorization" [22]. "BSF larvae feed voraciously on different organic wastes like animal manure *viz.* poultry, swine and dairy manure" [23-29]. Kitchen waste [30,31] Human faeces and fecal sludge [29,31,32,33,34,35,36], municipal organic waste [37], fruit and vegetable waste [38,39,40,41], spent grains [41], slaughterhouse waste, food processing waste [41,42], brewery waste and local beer waste [43], bakery waste [44]), and fish waste [28,37,45,46]. "Breakthrough research reveals that BSF larvae do not produce detectable methane emissions when fed various organic substrates" [47]. "This finding has significant implications for sustainable waste management and the transition to a circular bioeconomy. Bioconversion can be an effective and eco-friendly waste management and resource recovery technique to eliminate organic waste leading to a circular economy model. However, further research is crucial to optimize insect-based bioconversion processes for permanent organic waste elimination. By advancing this innovative approach, we can harness the potential of insect-based bioconversion to create a more sustainable and regenerative food system" [48]. "The conversion of food waste by BSF larvae is heavily influenced by presence of gut microbiota *viz*. Enterococcus, Klebsiella, *Morganella*, *Providencia*, and *Scrofimicrobium*, which play a vital role in substrate utilization" [49]. This highlights the importance of microbial communities in sustainable waste management and nutrient cycling.

"Composting using BSF requires a shorter time (12–15 days) than composting using microbes or earthworms" [50]. "BSF larvae can degrade organic waste up to 72% and the maturity of the compost is very precise" [51]. "ICAR-NBAIR has termed BSF compost as black gold due to its qualities. No significant changes in nutrient composition and compost-maintained shelf life under room temperature. The C:N ratio recorded from compost varied between 17.8- 22.0:1. The analysis of mature BSF compost revealed a humic substance content of 11.70% (w/w), moisture 26.05 % (w/w), organic matter 19.43% (w/w), pH of 7.19 and bulk density of 0.57 gmL-1" [52]. "BSF larvae can also reduce pathogen bacteria, such as *Escherichia sp., Salmonella sp., Vibrio sp., and Yersinia sp*., allowing the compost end product to meet the requirements for use as fertilizer and/or soil improver" [53]. "Some challenges arise regarding the use of BSF larvae as a bioconversion agent, such as for heavy metal residues, pesticide residues, pathogens, and antimicrobial gene transmission and residues that require the best composting strategy for mitigation" [54]. "Toxic elements can give bioaccumulation problems in BSF larvae and frass but the risk depends on their level in the growing substrate" [55].

4. BSF AS ANIMAL FEED

"In the field of animal nutrition, BSF larvae have emerged as a highly viable and sustainable source of protein. This species has attracted attention due to some special reasons which have the potency to convert waste food materials and manure into high quality insect proteins. The high protein content in BSF larvae, constituting up to 50% of their dry weight, makes them a potential sustainable alternative to traditional protein sources in animal feeds" [56]. "BSF gained special attention among the aquaculturists and it has been utilized for feed formulation in aquaculture. BSF larvae have an average content of 45.2% crude protein and 31.4% fat. However, fat and protein composition can vary as a function of growing substrate characteristics" [57]. "Maggots prefer to accumulate protein food residues rather than carbohydrate food residues" [58]. "They present an environmentally friendly alternative to conventional feed ingredients such as soybean meal and fishmeal" [59]. "BSF larvae meal showed a positive impact on improving health conditions in fishes by various workers" [60,61]. Linh et al. revealed that "fish meal can be effectively replaced by BSF larvae meal and that this not only has a positive effect on immune-related gene expression and growth rate growth rate in fishes" [62]. "Research has revealed the positive effect of BSF diet on broiler chickens [63-65]. Inclusion of live BSF larvae did not affect fear behavior in laying hens, but the relative abundance of certain gut microbiota was associated with fear-related behaviors" [66]. "BSF generates a sustainable protein source as well as the importance of its use as a substitute of protein-rich feedstuff in poultry feed manufacturing. Producing BSF on waste streams as protein component for feed can be done locally, generating a circular approach either to agriculture on-farm or in the local community thus generating an economy that is not dependent on external inputs. BSF has been identified as the most versatile because of the variety of biological wastes that can be used for its rearing, automation, scalability, nutritional value, and because of circular and environmental aspects" [67]. Studies by Perez-Velazquez et al. revealed that "the fish diets with the levels of replacement of 50% and 75%, with final weights of 23.04 and 23.11 g, respectively, elicited superior fish performance, as compared to the diet with 25% replacement (final weight of 20.09 g)" [68]. "BSF do not carry bacteria or diseases and larvae are capable of inactivating *Escherichia coli* and *Salmonella enterica"* [69]. "In the EU, insects have been allowed as protein sources for aquaculture since 2017" [70]. BSF is also used as ingredient in the food of pigs [71-72] turkey [73], rabbits [74-75], ducks [76]and quails [77].

5. BSF AS HUMAN FOOD

Edible insects can be used to solve the problem of food scarcity [78-79]. Food safety reports indicating the microbial risks associated with edible insect species based their suggested limits on EU safety regulations for meat and seafood, due to the high moisture and nutrient content of the insects [80-81]. Insects are not listed in the Codex Alimentarius, a United Nations document on what is considered "food" that informs much global food regulatory policy, except as impurities that contaminate food [82]. BSF do not concentrate pesticides or mycotoxins. For commercial use in human foods, larvae could potentially be milled and converted into a textured protein with a strong flavor [83]. BSF larvae and pupae are safe for humans to eat, their eggs are not. Few cases of enteric/intestinal myiasis caused by BSF maggots owing to the consumption of unwashed fruit on which BSF eggs were present, has been reported [84]. A case of cutaneous myiasis was also recorded due to the same reason [85]. However, this problem will be eliminated in case of dried, cooked, and/or powdered BSF products. Currently the regulations in the EU do not support the use of BSF maggots in human food [86].

6. BSF FOR CHITIN EXTRACTION

"Chitin is a linear polymer of N-acetyl-d-glucosamine. Chitin and chitosan find application in the food industry, agriculture, wastewater treatment, tissue engineering, biomedical, biotechnological, sanitary and cosmetic sectors, and in the textile and paper industries" [87,88]. "The chitin market is estimated to reach USD 2.941 billion in 2027" [89]. "Insect exoskeletons are rich in chitin. The exoskeleton of BSF contains up to 35% chitin" [90]. "Chitin can be extracted from each stage of BSF [91]. Also, pupal exuviae and dead adults of BSF are chitin-rich waste materials" [93]. "Therefore, continuous production of BSF can yield this high-quality biopolymer. BSF has an ability to produce chitin polymers or polymer of glucosamine up to 7% of BSF biomass on dry matter basis" [92]. Xiong et al. [95] designed "chitin extraction from pupae and puparium of BSF using microbial treatments" [93]. "Chitosan from BSF slows down the decay of strawberries [94]. Thus, by recycling wastes, ultimately leading to the production of chitin and chitosan polymers, BSF fits well with the principles of circular economy" [95-96].

7. BSF FOR BIODIESEL PRODUCTION

"Insect fat has been proposed as a promising resource for biodiesel production" [97]. "Biodiesel production from BSF can be achieved by lipid extraction or by transesterification" [98,99,100,101, 102]. "This consumes less energy and increases sustainability" [103]. "All the parameters of biodiesel produced from BSFL satisfied the Korea fuel standard except oxidation stability" [104]. "Worldwide research on BSF is on the right track towards the avenues of production of green bioenergy" [105].

8. CASE STUDIES

Chineme et al. investigated "how an open BSF biowaste system could apply circular economy principles to close a resource loop in a low-income community and highlights the benefits of adopting a modified circular economy in Kipunguni, Dar es Salam"[106]. Through community involvement, circular economy principles were effectively implemented to redirect a retail market's fruit and vegetable waste from the landfill. Corn bran was substituted by BSF larvae as animal feed, and frass biofertilizer replaced commercial fertilizer. Thus, demonstrating circularity in the study location. The free-range open system produced 19.15 kg of BSF larvae, with 44.34% protein content, 20.6% crude fat and zero heavy metals.

Using experimental and secondary data, Abro et al. assessed potential socio-economic benefits of BSF larvae meal to the Kenyan poultry sector [107]. They concluded that replacing 5-50% of the conventional feed sources by BSF can generate a potential economic benefit of 69-687 million USD (0.1-1% of the total GDP) and 16-159 million USD (0.02-0.24% of the GDP) if the entire commercial poultry sector adopts BSF larvae meal. These could translate to reducing poverty by 0.32-3.19 million (0.07-0.74 million) people, increasing employment by 25,000-252,000 (3300-33,000) people, and recycling of 2-18 million (0.24-2 million) tonnes of biowaste.

9. ASPECTS OF BSF BASED BUSINESS INDUSTRY

"There is increasing demand for protein-rich feed in animal industry, aquaculture, meat industry. Also, there is increasing government support for the use of insect meal in animal feeds. The BSF market is expected to reach $3.96 billion by 2033, at a CAGR of 31% from 2024–2033, while in terms of volume, the market is expected to reach 8.23 million tons by 2033, at a CAGR of 40.4% from 2024 to 2033. It is important to work on the legal framework and the harmonization of a differentiated legal status of insects as food and feed across the world to facilitate the global use of this sustainable source and promote investments on both household and industrial production" [108,109]. Research emphasis on establishing new supply chains to support entrepreneurs in finding solutions that can address logistical challenges to experiment with more efficient production scales in the BSF industry, which may increase in accessibility and competitiveness.

10. BSF FOR ACHIEVING SUSTAINABLE DEVELOPMENT GOALS (SDGs)

"SDGs target five critical areas: people, planet, prosperity, peace, and partnership, addressing pressing global challenges to ensure a better future for all These goals are No poverty (SDG 1), Zero hunger (SDG 2), Good health and well-being (SDG 3), Quality education (SDG 4), Gender equality (SDG 5), Clean water and sanitation (SDG 6), Affordable and clean energy (SDG 7), decent work and economic growth (SDG 8), industry, innovation and infrastructure (SDG 9), reduced inequalities (SDG 10), sustainable cities and communities

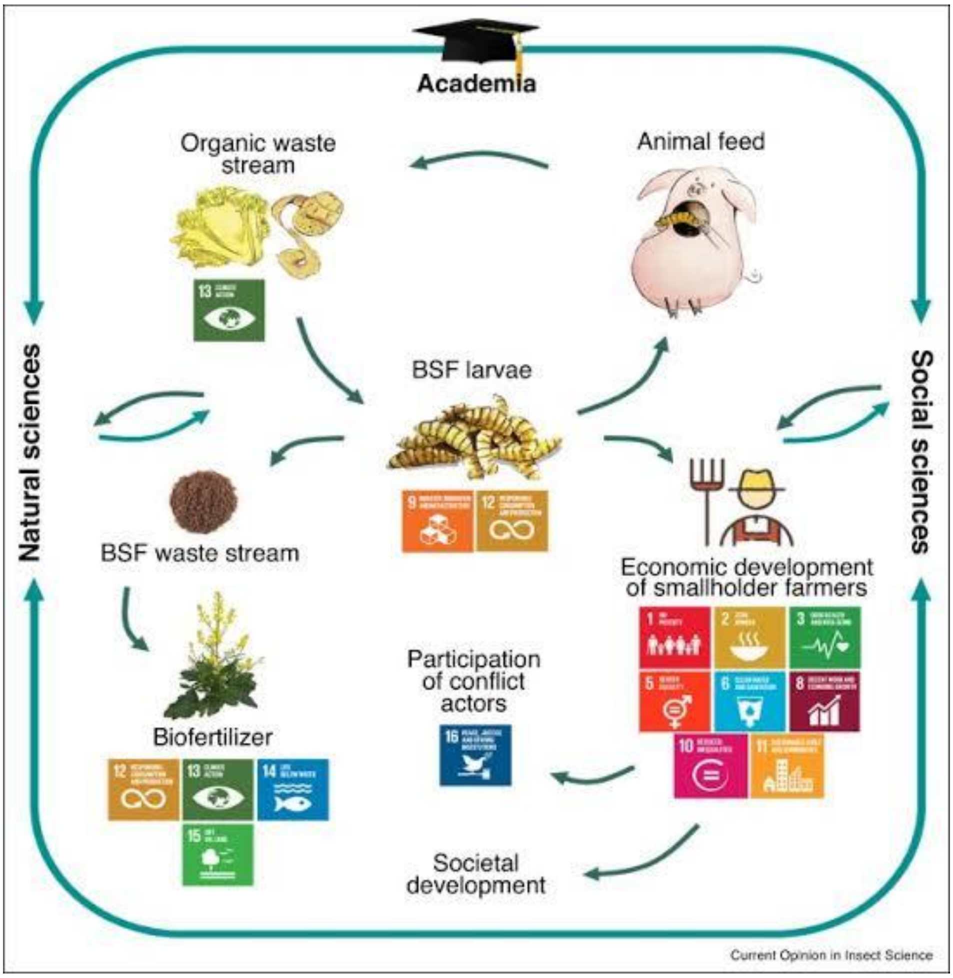

Fig. 2. Developing a circular economy based on the production of black soldier flies (BSF) [14]

(SDG 11), responsible consumption and production (SDG 12), climate action (SDG 13), life below water (SDG 14), life on land (SDG 15), peace, justice, and strong institutions (SDG 16) and partnerships for the goals (SDG 17)" [1]. "BSF farming is getting popularized nowadays as an innovative approach for waste to wealth, which is said to meet 12 out of 17 sustainable development goals (no poverty, zero hunger, good health and well-being, gender equality, clean water and sanitation, decent work and economic growth, industry, innovation and infrastructure, reduced inequalities, sustainable cities and communities, responsible consumption and production, climate action, life below water, life on land, peace, justice and strong institutions (Fig. 2)" [14].

11. BSF RESEARCH STATUS IN INDIA AND FUTURE PROSPECTS

In India, natural occurrence of BSF is reported previously by Ashuma et al. Gujarathi and Pejaver and Pathak et al in manure and compost. [110-112]. Sable et al. reported natural occurrence of BSF at 16 locations from 10 districts of Maharashtra and recorded various types of organic wastes utilized as feed by BSF in natural settings [113]. The biology of BSF is studied by Sharanbasappa et al. on muskmelon [114]; Khyade (2021) on kitchen waste [115]; Shrikant and Sharanbasappa on organic wastes [116], Sable and Tawale on fruit and vegetable wastes [40] and Sable et al on kitchen waste [113] . Bioconversion efficiency of BSF was studied on various organic waste streams by Singh et al. [117] Ganvir et al. [44] and Karthkeyani et al. [32]. Naik and Katkar proposed the BSF technique for waste management [118].

India faces the problem of huge amount of organic waste residues in rural and urban areas and BSF can be employed for the management of these residues. Small and medium holding farmers, poultry farmers and aquaculturists, can adopt the production of BSF on household kitchen waste and agricultural waste. BSF is currently mass produced as feed on a large scale in China, USA, Canada, South Africa and several European countries [119]. Similarly, BSF will be helpful for small holder and medium holding farmers in India. It is highly essential to explore the potential of BSF in India for waste management, compost making and animal feed production.

12. CONCLUSIONS

The global challenges of organic waste generation, pollution, and costly animal feed necessitate innovative solutions. BSF larvae provide a sustainable answer, transforming organic waste into valuable compost and animal feed. Implementing BSF-based systems can significantly mitigate waste management issues, environmental pollution, and greenhouse gas emissions. The insect's high reproductive rate, adaptability, and nutritional value make it an attractive option for large-scale production. Studies have demonstrated its potential for compost, chitin, biodiesel production and even human nutrition. Overall, BSF research highlights its vast potential for contributing to circular economy. Potential of BSF can be harnessed to achieve sustainable development goals. However, further research is needed to optimize breeding, rearing, and processing techniques. Standardization of protocols and regulations is also essential for industrial-scale implementation. There is a scarcity of BSF research in India and the potential of BSF as feed food and composting agent in India remains unexplored. There is great scope for utilization of BSF for wellbeing of small and medium holding farmers. India's tropical climate, abundant organic waste, and growing demand for sustainable solutions make it an ideal location for BSF-based industries to thrive.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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