PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 11(sp4): 01–08
https://doi.org/10.14719/pst.5652

HORIZON
e-Publishing Group
HePG

RESEARCH ARTICLE

Unravelling the role of Black Soldier Fly Frass (BSFF) in nutrient enrichment and growth promotion of groundnut (*Arachis hypogaea* L.)

S Raman[1], G Srinivasan[1*], M Shanthi[2], S Saravanan[3] & ML Mini[4]

[1] Agricultural Entomology, Department of Agricultural Entomology, Agricultural College and Research Institute, Madurai 625 104, Tamil Nadu, India

[2] Centre for Plant Protection Studies, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[3] ICAR-Krishi Vigyan Kendra, Agricultural College and Research Institute, Madurai 625 104, Tamil Nadu, India

[4] Department of Biotechnology, Agricultural College and Research Institute, Madurai 625 104, Tamil Nadu, India

*Email: srinivasan.govindaraj@yahoo.com

OPEN ACCESS

ARTICLE HISTORY
Received: 09 October 2024
Accepted: 23 October 2024
Available online
Version 1.0 : 11 December 2024

Check for updates

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

CITE THIS ARTICLE
Raman S, Srinivasan G, Shanthi M, Saravanan S, Mini ML. Unravelling the role of Black Soldier Fly Frass (BSFF) in nutrient enrichment and growth promotion of groundnut (*Arachis hypogaea* L.). Plant Science Today.2024;11(sp4):01-08. https:/doi.org/10.14719/pst.5652

Abstract

The decomposition of organic waste by Black Soldier Fly (BSF) plays a potential role in plant growth promotion and soil nutrient enrichment. This study investigated the effect of different compost from food waste, vegetable & fruit waste, cow manure, pig manure, poultry manure, TNPL (Tamil Nadu Newsprint and Papers Limited) bio sludge and combinations of these materials induced varied growth promotion on groundnut. A pot culture experiment evaluated shoot length, root length, germination percentage, plant biomass and vigour index. The best results were observed in the treatment combining hostel food waste and vegetable waste (50 %) with poultry manure (50 %) (T_7), showing a shoot length of 20.34 cm, vigour index of 3629, plant biomass of 24.3 g, and germination percentage of 93.33%. Other treatments, such as food waste (T_1) and vegetable and fruit waste (T_2), showed vigour indices of 2561.6 and 2692.9, respectively, while the untreated control had the lowest vigour index of 900.4. Nutrient analysis of T_7 compost revealed high levels of nitrogen (462 kg/ha), phosphorus (375 kg/ha), potassium (320 kg/ha) and micronutrients like iron (29.04 ppm) and zinc (7.58 ppm). GC-MS analysis identified growth-promoting compounds like Cyclohexanol (64.3 %), Glycerol (3.9 %) and Dibutyl phthalate (1.49 %). Metabolite set enrichment analysis (MSEA) highlighted pathways like fatty acid biosynthesis and glycerolipid metabolism, which support root development and stress tolerance. The results indicated that BSF compost, especially from food and vegetable waste with poultry manure, significantly enhances soil fertility and plant growth, providing a sustainable solution for organic waste management.

Keywords

BSF frass; groundnut; metabolite profiling; nutrient potentiality; organic waste decomposition; vigor index

Introduction

The larvae of *Hermetia illucens*, commonly called Black Soldier Fly (BSF), are employed for the bioconversion of various organic wastes (1). This process allows for significant waste reduction, potentially lowering organic waste by over 50 percent in a shorter timeframe than traditional composting methods. Various research indicates that BSF larvae can reduce food waste mixtures from 65.5 to 78.9 % per cent (2) and manure waste by up to 56 % (3). Additionally, a combination of food waste and human faeces saw a 68 per cent reduction (85 %

on a wet basis) (4). This method, when used sustainably, has the potential to decrease landfill waste significantly (5). Additionally, the byproducts from the decomposition of waste by BSF larvae can serve as fertilizer and soil enhancers, while the larvae can be processed into animal feed (6). The application of BSF for organic waste decomposition, particularly the use of BSFF Fertilizer (BSF Frass), along with the liquid derived from the bioconversion process, known as micro biostimulant (MBS), has been shown to boost plant growth (7).

Frass holds great potential as a valuable biofertilizer for plants, enhancing soil nutrient content with direct effects on plant growth and improving physical soil properties like structure, which indirectly supports plant development (8). BSF frass is becoming increasingly popular as an organic fertilizer due to its high levels of essential plant nutrients and chitin, a component of insect exoskeletons that appears to activate plant defence responses and promote growth (9). Frass is regarded as a beneficial biofertilizer, showing performance comparable to organic fertilizers, even when BSFLs are reared on different substrates. However, frass is not a standardized product; its quality and composition significantly influence the substrates used during larvae rearing (10). These variations in frass properties have notable effects on plant growth (11). Using insect BSFL frass as an organic fertilizer is a relatively new concept. Introducing any new product into agricultural systems requires extensive research and comprehensive knowledge to understand its potential for enhancing soil fertility and crop yields. BSFL frass with a commercial organic fertilizer on maize, showing its positive impact on plant height, chlorophyll levels and grain yield (12). On a more positive note, research by Composted BSFL frass can significantly enhance the growth of various plants, including French beans, tomatoes and kale (13).

During fattening, BSF larvae release enzymes and microbes that break down substrates more efficiently, converting them into valuable frass or compost faster than traditional composting while producing a higher quality output. This output can be utilized as Plant Growth-Promoting Rhizobacteria (PGPR). BSF frass as an organic fertilizer has become increasingly common due to its ability to enhance nitrogen uptake in plants, leading to more efficient use of nitrogen fertilizers (13). The PGPR, particularly those from the genus *Enterococcus*, which have been previously identified in decaying waste feedstocks and the larval gut of BSFL and are capable of colonizing plant roots are of significant interest due to their potential role in imparting growth-promoting properties to frass (14, 15).

However, there is still limited knowledge regarding the plant growth-enhancing potential of BSF larval frass derived from various substrates and their associated mineral nutrients. This study focuses on the role of BSF frass from different organic substrates in promoting groundnut plant growth, with bioactive metabolites analyzed through GC-MS and examines the impact on soil nutrient enrichment.

Materials and Methods

Different substrate decomposing through BSF

The nutrient potentiality and growth promotion of various substrates decomposed by Black Soldier Fly (BSF) were tested on groundnut plants. The treatments included food waste (Hostel) (T_1), vegetable and fruit waste (Hostel) (T_2), cow manure (T_3), pig manure (T_4), poultry manure (T_5), cow manure (50 %) + poultry manure (50 %) (T_6), hostel food and vegetable waste (50 %) + poultry manure (50 %) (T_7), TNPL Bio sludge (T_8) and TNPL Bio sludge (40 %) + poultry manure (60 %) (T_9). These decomposed frasses were tested for their nutrient potentiality and effect on groundnut plants' growth promotion.

Growth promotion assay

A pot culture experiment was conducted to study the effect of various composts on the plant growth of groundnut. The treatments included food waste (hostel), vegetable and fruit waste (hostel), cow manure, pig manure, poultry manure, TNPL bio sludge and combinations of these organic materials in different proportions. An untreated group was maintained as the control. Each treatment was applied uniformly to the plants and growth parameters such as shoot length (cm), root length (cm), germination percentage (%), plant biomass (g) and vigour index were calculated following the method (16).

The vigour index was calculated using the formula as given in Equation 1.

Vigor Index = Germination % × mean total length of the seedling (root length + shoot length) (Eqn. 1.)

The data were analyzed statistically to determine the impact of the treatments on overall plant growth and performance.

Solvent extraction of compost through Soxhlet apparatus

The bioactive compounds in the substrate where BSF larvae were grown were extracted using the Soxhlet extraction method. The bioactive compounds in the substrate where BSF larvae grew were extracted using the Soxhlet extraction method (17). About 10 g of compost was placed in the thimble, which was drawn into a distillation flask with 150 mL of solvent n–hexane (n–hexane has a low boiling point, high oil solubility and high oil extraction percentage). Finally, the solvent reached the overflow level; the solution was sucked from the thimble holder *via* a siphon pipe, which released the solution back into the distillation flask. The process was repeated until the bioactive compounds were extracted into the solvent (1–6 hr).

GC-MS analysis of BSF frass

The solvent containing bioactive compounds was filtered through Whatman No.1 filter paper. The sample was concentrated in a vacuum rotary evaporator (at 80 RPM with 60 °C) until the solvent evaporated. The extracellular antifungal compounds containing concentrated crude metabolites were dissolved in 2mL of methanol. Finally, the antifungal compounds of the extract were focused on the rotary flask evaporator at 80rpm with 60 °C. The extracellular antifungal compounds containing concentrated crude metabolites were dissolved in 1 mL of methanol.

Methanol extracts of compost containing plant growth –promoting secondary metabolites were analyzed using a

Shimadzu Gas Chromatography system equipped with a Turbo Mass Gold mass detector and an Elite–1 (100 % Dimethyl Polysiloxane) column, measuring 30 m × 0.25 mm ID × 1 mm df. The analysis was conducted under the following conditions: helium was used as the carrier gas at a flow rate of 1 mL/min, and the oven temperature was programmed to rise from 110 °C (held for 2 min) to 280 °C (held for 9 min). The injector temperature was set at 250 °C, with a total GC run time of 45 min. A 1.0 mL aliquot of the methanol extract was injected for analysis. The principal compounds were identified using a computer-driven algorithm and the mass spectra were compared with the NIST library (Version 2.0, Year 2005). Turbo Mass version 5.1 software was employed to perform the GC-MS analysis (18).

Metabolite set enrichment analysis of BSF frass GC–MS results.

The GC–MS analysis identified 25 important plant growth–promoting compounds, and their enriched pathways were constructed using the MetaboAnalyst software. Metabolite Set Enrichment Analysis (MSEA) was used to identify significant patterns in metabolomic data without relying on arbitrary significance cutoffs. Unlike conventional approaches that evaluated metabolites individually, MSEA analyzed groups of functionally related metabolites, uncovering subtle but consistent changes. MSEA uses standardized compound labels and databases like HMDB, PubChem and KEGG to map compounds, ensuring precise identification for enrichment analysis. This approach revealed the prominent role of fatty acid biosynthesis in BSF frass (19).

Estimation of nutrient enrichment by using BSF frass

To understand the nutrient status of the frass, the macro and micronutrients were estimated from the performed BSF decomposed frass. The compost samples were shade-dried, gently powdered with a wooden mallet and sieved through a 2 mm sieve. These samples were analyzed for pH, EC, available nutrients and micronutrients following standard procedures. pH was measured in a 1:2 soil-water suspension using a pH meter, while EC was determined with a conductivity meter. Organic carbon content was assessed using the chromic acid wet digestion method. Available nitrogen was estimated using the alkaline potassium permanganate method (20) and phosphorus content was determined colourimetrically using the ascorbic acid method at 660 nm (21). Potassium was extracted with neutral standard ammonium acetate (NH_4OAc) and measured using a flame photometer (22). Micronutrients such as Fe, Mn, Zn and Cu were extracted using Diethylenetriaminepentaacetic acid (DTPA) and analyzed using an Atomic Absorption Spectrophotometer (Thermo Scientific, ICE 3000 series).

Statistical analysis

The statistical analysis was conducted using AGRES (Statistical package of TNAU) to analyze variance (ANOVA). A Completely Randomized Design (CRD) was employed for the *in–vitro* investigations. The data were subjected to ANOVA at a significance level of P=0.05 and the averages were compared using Duncans' Multiple Range Test (DMRT), following the method outlined (23).

Results and Discussion

The experiment analyzed the effect of various treatments on shoot length, root length, germination percentage, plant biomass and the vigour index of groundnut plants. Notably, the compost frass used in these treatments was derived from composting processes where Black Soldier Fly (BSF) larvae were naturally present, aiding in organic waste breakdown. The highest shoot length was recorded for the treatment T_7 (Hostel food and vegetable waste combined with poultry manure), which achieved 20.34 cm, with a corresponding vigour index of 3629.0. This treatment also showed the highest plant biomass at 24.3 g and a germination percentage of 93.33 %. T_1 (Food waste from the hostel) had a shoot length of 15.6 cm, with a plant biomass of 22.5 g, leading to a vigour index of 2561.6. Similarly, T_2 (Vegetable and fruit waste from the hostel) exhibited a shoot length of 13.7 cm and a vigour index of 2692.9, supported by a germination rate of 86.66 %. Treatments like T_3 (Cow manure) and T_4(Pig manure) produced moderate results, with shoot lengths of 11.76 cm and 11.64 cm, respectively, along with moderate biomass and vigour index.

On the other hand, the untreated group showed the lowest vigour index (900.4), with a short length of only 8.54 cm and a biomass of 14 g, indicating limited growth performance without treatment. In contrast, treatments combining cow and poultry manure (T_6) and bio sludge (T_8, T_9) showed mixed results, with shoot lengths ranging from 8.54 cm to 15.75 cm and vigour indices below 1600. The nutrient-rich compost, enhanced by BSF larvae activity, likely contributed to the superior performance of the hostel food waste-based treatments, suggesting that the larvae improved the frass effectiveness in promoting plant growth (Fig. 1.).

These findings are consistent with previous research. BSF frass application improved plant growth in corn and Pak Choi compared to control treatments (7). Applying 50 % BSF frass resulted in superior plant performance, supporting the results of the current experiment. Similarly, adding 10 g/L of BSF frass to basil (*Ocimum basilicum*) plants increased fresh biomass by 30 % and enhanced photosynthetic activity, particularly under drought conditions (24). This study emphasizes that BSF frass provides nutrients and enhances plant resilience to environmental stresses, which may explain the robust growth observed in groundnut plants treated with BSF frass. BSF frass offers essential nutrients and biostimulants, such as chitin and humic substances, which enhance plant tolerance to abiotic stresses like drought and salinity (25). It promotes beneficial microbial activity, improving soil health and facilitating nutrient uptake under stress conditions.

Additionally, amino acids and phytohormones strengthen plants' immune systems, enabling them to withstand environmental stressors better. Moreover, BSF frass improves soil structure and water retention capacity, aiding plants during water scarcity, and its antimicrobial properties protect plants from soil-borne pathogens, reducing infection-induced stress (26). Further, it highlights the potential of BSF frass as an effective fertilizer (12). Their research on maize revealed that applying 2.5 tons of BSF frass per hectare enhanced plant height by 10-15 %, yield by 20 % and root

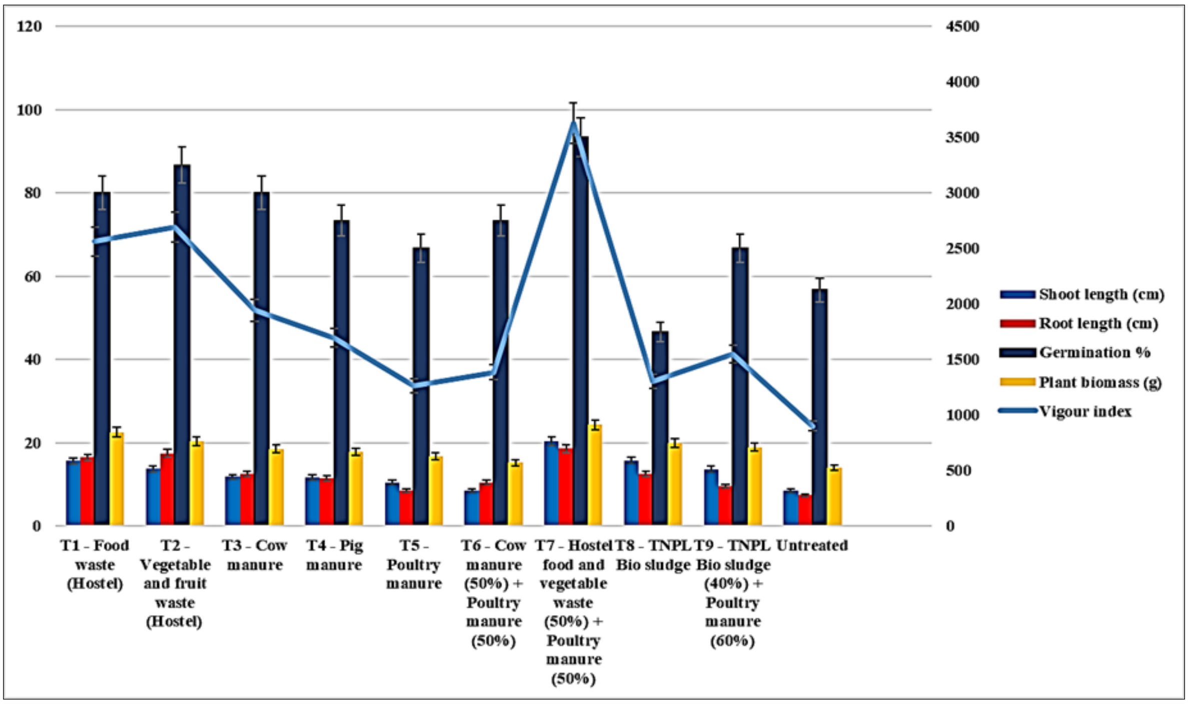

Fig. 1. Growth promotion of groundnut on different BSF frass.

biomass by 18 %. These findings indicated that BSF frass was an effective alternative to conventional fertilizers, especially in nutrient–deficient soils with limited access to chemical fertilizers.

Similarly, BSF frass application improved wheat productivity by 14 %, increased organic carbon content by 10 %, water retention by 6 % and reduced soil compaction by 12 % (27). These benefits contributed to a 17 % increase in root biomass, reflecting the enhanced nutrient absorption capabilities observed in the present studys' treatments. In rice cultivation, a 15 percent increase in yield with the application of 3 tons of BSF frass per hectare, attributing the improvement to consistent nutrient release throughout the growing season. Their study also showed an 18 % enhancement in root development, allowing for more efficient nutrient uptake during critical stages such as tillering and grain filling. These findings are particularly relevant to the current experiment, where BSF frass treatments significantly improved nutrient uptake and root development. Overall, this experiment confirms that BSF frass is a highly effective organic amendment for promoting plant growth in groundnut crops. The results strongly suggest that frass produced by BSF larvae during the composting process enhances nutrient availability and contributes significantly to improved plant growth parameters, particularly in shoot length, biomass and vigour index.

The GC–MS analysis of the BSF compost treatment T_7, consisting of a 50 % mixture of hostel food and vegetable waste and 50 % poultry manure analysis, revealed several metabolites related to the identified metabolites. Further pathway analysis suggested their potential roles in nutrient cycling and growth promotion in groundnut. The biosynthesis of unsaturated fatty acids, with two hits and a significant P value of 0.00753, suggests the active production of fatty acids essential for cell membrane formation and energy storage, which can enhance root development and stress tolerance in groundnut plants. Pathways such as glycerolipid and propanoate metabolism are linked to energy production and efficient carbon utilization, promoting plant growth by enhancing metabolic efficiency (Fig. 2.). Additionally, identifying fatty acid elongation and degradation pathways indicates lipid metabolism, crucial for maintaining membrane integrity and providing precursors for signalling molecules that can promote nutrient uptake and stress resistance. These metabolites in the compost contribute to improved soil fertility, enhanced nutrient availability and overall better plant vigour, leading to improved growth in groundnut.

The bioactive compounds cyclohexanol (cis-and trans-) were detected at 5.411 min (7.95 %) and 5.613 min (64.3 %), which supports stress tolerance and membrane structure. At 6.321 min (1.22 %), Alpha-D-galactopyranoside aids in carbohydrate metabolism for energy storage. Silanol (6.406 min, 0.29 %), 1,1–Dimethylethanol (7.732 min, 0.59 %) and 2 Isopropyl(dimethyl)silyloxypropane (8.364 min, 0.19 %) enhance membrane stability and lipid metabolism. Glycerol (11.55 min, 3.9 %) and acetic acid (11.795 min, 0.29 %) promote lipid biosynthesis and energy metabolism. Propanoic acid (21.395 min, 0.27 %) and Tetradecane (24.453 min, 0.23 %) support fatty acid biosynthesis. Dibutyl phthalate (31.337 min, 1.49 %) and Palmitic acid (33.37 min, 0.85 %) maintain membrane integrity and nutrient uptake, while 3–Trifluoroacetoxypentadecane (36.812 min, 0.22 %) contributes to fatty acid metabolism. These compounds enhance stress resistance, nutrient cycling, and plant growth, making the compost highly beneficial for soil fertility and plant development (Table 1 and Fig. 3.).

Similarly, BSFL frass improved wheat growth by 11 % despite low nitrogen levels, phytohormones and biogenic amines (29). HPLC and GC-MS revealed only trace amounts of these compounds, which did not explain the growth benefits. However, the presence of viable *Enterococci* in the frass, confirmed through BEA plate cultures, suggested that microbial interactions, particularly with rhizobacteria, significantly promoted plant growth. The GC–MS results also

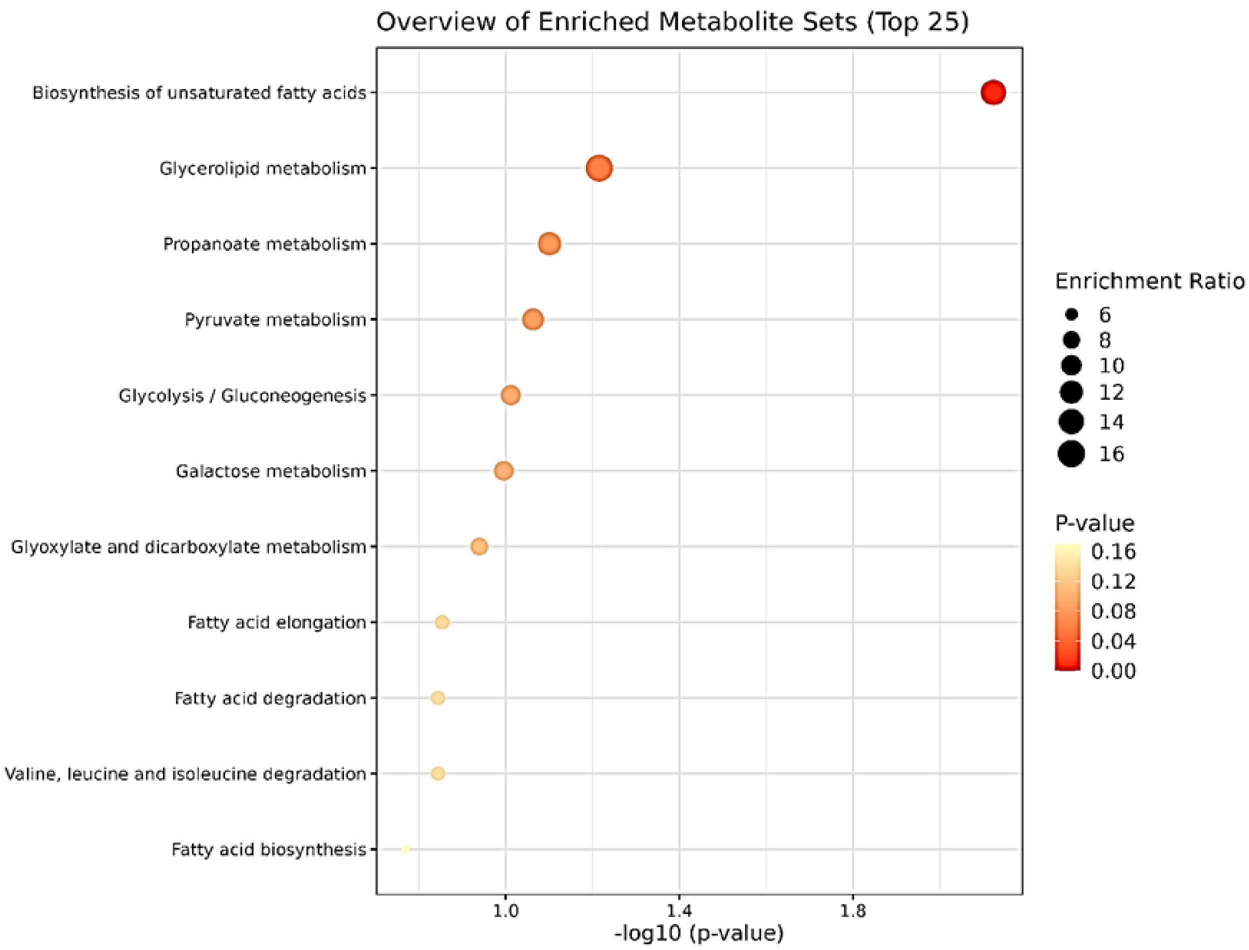

Fig. 2. Pathway enrichment analysis of metabolites from BSF frass through GC–MS analysis.

Table 1. Plant growth promoting metabolites of compost [T_7 - Hostel food waste and vegetable waste (50 %) + Poultry manure (50 %)] and their peak area percentage, retention time obtained from GC–MS analysis

S.No	Compound Name	RT (min)	Peak Area (%)	MW (g/mol)	Chemical Formula	Plant Growth Promotion Role	References
1	Cyclohexanol, 2–(trimethylsilyl)-, cis-	5.411	7.95	172.33	$C_9H_{20}OSi$	Stress tolerance, metabolism	(36)
2	Cyclohexanol, 2–(trimethylsilyl)–, trans –	5.613	64.3	172.33	$C_9H_{20}OSi$	Membrane structure	(36)
3	Alpha–D–galactopyranoside, methyl 2,6–bis–O–(trimethylsilyl)–, cyclic phenyl boronate	6.321	1.22	482.69	$C_{21}H_{35}BO_7Si_2$	Carbohydrate metabolism	(37)
4	Silanol, (1,1–dimethyl ethyl) dimethyl	6.406	0.29	146.29	$C_6H_{16}OSi$	Stress tolerance, membrane stability	(38)
5	1,1–Dimethylethanol, TMS derivative	7.732	0.59	176.33	$C_6H_{18}OSi$	Membrane stability	(38)
6	2Isopropyl (dimethyl) silyloxypropane	8.364	0.19	190.35	$C_8H_{20}OSi$	Lipid metabolism	(39)
7	Glycerol, 3TMS derivative	11.55	3.9	308.61	$C_9H_{24}O_3Si_3$	Lipid biosynthesis	(36)
8	Acetic acid, 2–[2–[(trimethylsilyl)oxy] ethoxy]–, trimethylsilyl ester	11.795	0.29	264.47	$C_{10}H_{24}O_4Si_3$	Energy metabolism	(40)
9	2–[(Trimethylsilyl)oxy] propan–1–ol	12.111	2.46	190.35	$C_7H_{18}O_2Si$	Lipid metabolism	(39)
10	Propanoic acid, decyl ester	21.395	0.27	214.35	$C_{13}H_{26}O_2$	Fatty acid biosynthesis	(39)
11	Tetradecane	24.453	0.23	198.39	$C_{14}H_{30}$	Lipid biosynthesis	(40)
12	1–Dodecanol	25.659	0.12	186.34	$C_{12}H_{26}O$	Water retention	(38)
13	Dibutyl phthalate	31.337	1.49	278.35	$C_{16}H_{22}O_4$	Membrane integrity	(38)
14	Palmitic Acid, TMS derivative	33.37	0.85	256.43	$C_{16}H_{32}O_2$	Membrane integrity, nutrient uptake	(39)
15	3–Trifluoroacetoxypentadecane	36.812	0.22	330.44	$C_{17}H_{31}FO_2$	Fatty acid metabolism	(41)

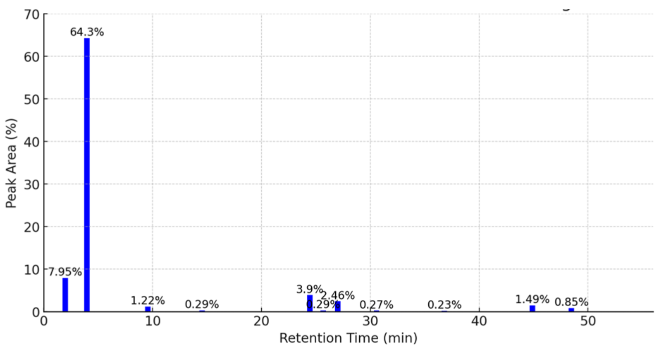

Fig. 3. Chromatogram of GC-MS analysis of compost (T_7 - Hostel food and vegetable waste (50 %) + Poultry manure (50 %) obtained from BSF.

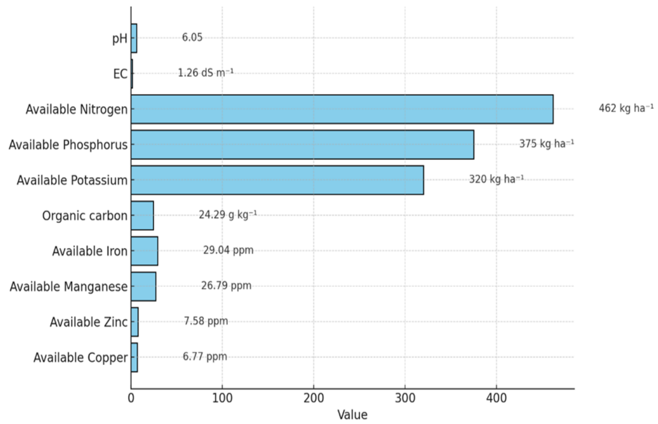

Fig. 4. Nutrient analysis of compost frass T_7 (Hostel food and vegetable waste (50 %) + poultry manure (50 %)) obtained from BSF.

identified key metabolites in BSFL frass, including cyclohexanol, glycerol, acetic acid and palmitic acid, which enhanced lipid metabolism, nutrient uptake and stress tolerance. These findings highlight the potential of BSFL frass to improve plant-microbe interactions, nutrient cycling, and overall plant health, making it effective in promoting soil fertility and growth.

The nutrient analysis of BSF compost frass T_7 (Hostel food and vegetable waste (50 %) + Poultry manure (50 %)) reveals a nutrient-rich composition that is highly beneficial for groundnut cultivation. This compost improves the soil texture of sandy clay loam, providing excellent drainage and aeration, which is ideal for groundnut root development. With a slightly acidic pH of 6.05, the compost falls within the optimal range for groundnut growth. Electrical conductivity (EC) is 1.26 dS m^{-1}, indicating manageable salt levels, which is critical for the germination of groundnut seeds. The compost frass boasts high levels of essential macronutrients, with available nitrogen at 462 kg/ha, phosphorus at 375 kg/ha, and potassium at 320 kg/ha. These high nitrogen, phosphorus and potassium concentrations are particularly valuable for groundnut plants, promoting strong vegetative growth, root development and pod formation. Organic carbon content is also high at 24.29 g/kg, enhancing soil structure, water retention and microbial activity, which are crucial for healthy groundnut growth. Additionally, micronutrients such as iron (29.04 ppm), manganese (26.79 ppm), zinc (7.58 ppm), and copper (6.77 ppm) are present in sufficient amounts, ensuring that groundnut plants receive a balanced supply of trace elements necessary for enzyme functions, disease resistance, and overall plant health. This nutrient profile indicates that the BSF compost frass can significantly improve soil fertility and support higher yields and healthier groundnut crops (Fig. 4.).

BSF frass is a nutrient-rich organic fertilizer with improved NPK values, typically containing 4-6 % nitrogen (N), 2-3 % phosphorus (P) and an elevated 3-4 % potassium (K), making it particularly effective for enhancing soil potassium levels. This high potassium content plays a crucial role in strengthening plant cell walls, improving root development and boosting water retention capabilities in soil. Increased potassium availability enhances plant resilience to abiotic stresses such as drought, salinity and temperature fluctuations, enabling better osmotic regulation and nutrient transport (30). BSF frass improves soil quality by supplying approximately 40-60 kg of nitrogen (N), 20-30 kg of phosphorus (P) and 30-40 kg of potassium (K) per hectare, depending on the application rate. This nutrient enrichment enhances soil fertility, promotes plant growth and provides an effective way to recycle organic waste into sustainable fertilizer (31).

The findings from various studies highlight the significant benefits of Black Soldier Fly (BSF) frass in enhancing plant growth and soil health across different crops. The broader effects of BSF frass in corn production increased soil organic matter by 8 % and improved root structure and density by 15 % (32). These improvements led to better nutrient and water use efficiency, with frass–treated soils experiencing a 10 % increase in microbial biomass, supporting nutrient cycling and soil health. This underscores the value of BSF frass beyond mere nutrient provision, contributing to a healthier soil ecosystem overall. Similarly, BSF frass could reduce the need for chemical fertilizers by up to 40 %, making it a sustainable option for organic farming (33). Their study also revealed an 18 % reduction in production costs while maintaining or improving crop yields, positioning BSF frass as an essential component in shifting toward eco–friendly agricultural practices, particularly in areas impacted by excessive chemical fertilizer use. A pot experiment on *Pakchoi* (*Brassica rapa*) (13). They demonstrated that compost+LOB, compost and BSF frass treatments significantly increased biomass, with the highest plant weight recorded in the compost + LOB treatment (24.4 g) and 10 % BSF frass (23.3 g). Although chlorophyll content remained relatively unchanged, BSF frass–treated plants exhibited curly leaf symptoms. Notably, BSF frass treatments showed higher levels of P-solubilizing bacteria and PME–ase enzyme activity than control and NPK treatments, confirming its advantages as a soil amendment.

In maize production, Black Soldier Fly Frass Fertilizer (BSFFF) significantly enhanced maize growth, yield and nitrogen use efficiency compared to NPK, brewers' spent grain (BSG) and Evergrow® (35). Maize grain yield increased by 2-25 %, 25-113 % and 153-212 % with BSFFF over NPK, BSG and Evergrow, respectively and nitrogen use efficiency was 2-3 times higher than with BSG and Evergrow. BSFFF also improved maizes' crude protein and fibre content when combined with NPK. The combination of BSFFF and NPK generated 2-173 % higher net income than sole NPK, BSG-NPK mixtures, or BSFFF alone. These findings highlight the potential of BSFFF, either alone or integrated with NPK, as a sustainable fertilizer option to enhance maize production, improve food security and support smallholder livelihoods while promoting environmental sustainability. Finally, the nutrient-rich composition of *Hermetia illucens* frass is derived from larvae fed on various substrates (35). The frass contained 2.1-3.8 % nitrogen, 0.8-1.3 % phosphorus and 1.2-1.7 % potassium, with pH levels ranging from 6.2 to 7.4 and moisture content between 45-70 %. The bacterial composition, including *Bacillus* and *Pseudomonas*, varied based on the feeding substrate, contributing to improved soil fertility. When applied, the frass significantly promoted the growth of leafy vegetables, cereals and legumes, further illustrating its agricultural benefits. Collectively, these studies confirm the multifaceted value of BSF frass in agriculture, not only as a nutrient source but also as a contributor to soil health, economic viability and sustainability.

Conclusion

BSF frass, particularly from food and vegetable waste combined with poultry manure, significantly enhances groundnut growth and soil fertility. The frass promotes shoot length, biomass and vigour index, with nutrient analysis revealing high levels of essential macronutrients and beneficial microbial activity. GC-MS analysis identified growth –promoting compounds that improve nutrient cycling and stress tolerance. BSF frass is a highly effective biofertilizer, offering a sustainable alternative to conventional fertilizers while promoting soil health and crop productivity.

Authors' contributions

SR carried out the lab experiment and did the statistical analysis. GS conceived and designed the experiment. MS, SS and MLM revised and finalized the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issue: None

References

1. Amrul NF, Kabir Ahmad I, Ahmad Basri NE, Suja F, Abdul Jalil NA, Azman NA. A review of organic waste treatment using black soldier fly (*Hermetia illucens*). Sustainability. 2022;14(8):4565. https://doi.org/10.3390/su14084565
2. Diener S, Studt Solano NM, Roa Gutiérrez F, Zurbrügg C, Tockner K. Biological treatment of municipal organic waste using black soldier fly larvae. Waste and Biomass Valorization. 2011;2:357-63. https://doi.org/10.1007/s12649–011–9079–1
3. Newton LA, Sheppard CR, Watson DW, Burtle GA, Dove RO. Using the black soldier fly, *Hermetia illucens*, as a value-added tool for the management of swine manure. Animal and Poultry Waste Management. 2005;17:18.
4. Dortmans B. Valorisation of Organic Waste - Effect of the feeding regime on process parameters in a continuous black soldier fly larvae composting system. 2015 Master' thesis, SLU, Swedish University of Agricultural Sciences, Uppsala, Sweden.
5. Nguyen TT, Tomberlin JK, Vanlaerhoven S. Ability of black soldier fly (Diptera: Stratiomyidae) larvae to recycle food waste. Environmental Entomology. 2015;44(2):406-10. https://doi.org/10.1093/ee/nvv002
6. Alvarez L. The role of black soldier fly*, Hermetia illucens* (L.) (Diptera: Stratiomyidae) in sustainable waste management in Northern Climates. 2012 Electronic Theses and Dissertations. University of Windsor, Ontario, Canada. 402.
7. Susanto M, Kurniawan S, Ricardi DE, Rianne W, Hersade D. Bioconversion and decomposing with black soldier fly to promote plant growth. KnE Life Sciences. 2022:681-92. https://doi.org/10.18502/kls.v7i3.11172
8. Chavez M, Uchanski M. Insect left–over substrate as plant fertilizer. Journal of Insects as Food and Feed. 2021;13;7(5):683–94. https://doi.org/10.3920/JIFF2020.0063
9. Sharp RG. A review of the applications of chitin and its derivatives in agriculture to modify plant–microbial interactions and improve crop yields. Agronomy. 2013;3(4):757-93. https://doi.org/10.3390/agronomy3040757
10. Klammsteiner T, Turan V, Fernández–Delgado Juárez M, Oberegger S, Insam H. Suitability of black soldier fly frass as soil amendment and implication for organic waste hygienization. Agronomy. 2020;10(10):1578. https://doi.org/10.3390/agronomy10101578
11. Song S, Ee AW, Tan JK, Cheong JC, Chiam Z, Arora S, Lam WN, Tan HT. Upcycling food waste using black soldier fly larvae: Effects of further composting on frass quality, fertilizing effect and its global warming potential. Journal of Cleaner Production. 2021;288:125664. https://doi.org/10.1016/j.jclepro.2020.125664
12. Beesigamukama D, Mochoge B, Korir NK, Fiaboe KK, Nakimbugwe D, Khamis FM, Subramanian S, Dubois T, Musyoka MW, Ekesi S, Kelemu S. Exploring black soldier fly frass as novel fertilizer for improved growth, yield, and nitrogen use efficiency of maize under field conditions. Frontiers in Plant Science. 2020;11:574592. https://doi.org/10. 3389/fpls.2020.574592
13. Agustiyani D, Agandi R, Arinafril, Nugroho AA, Antonius S. The effect of application of compost and frass from Black Soldier Fly Larvae (*Hermetia illucens* L.) on growth of Pakchoi (*Brassica rapa* L.). Earth and Environmental Science. 2021; 762:012036ng. https://doi.org/10.1088/1755– 1315/762/1/012036
14. Zhineng Y, Ying M, Bingjie T, Rouxian Z, Qiang Z. Intestinal microbiota and functional characteristics of black soldier fly larvae (*Hermetia illucens*). Annals of Microbiology. 2021;71:1-9. https://doi.org/10.1186/s13213–021–01626–8
15. Strafella S, Simpson DJ, Yaghoubi Khanghahi M, De Angelis M, Gänzle M, Minervini F, Crecchio C. Comparative genomics and in vitro plant growth promotion and biocontrol traits of lactic acid bacteria from the wheat rhizosphere. Microorganisms. 2020;9(1):78. https://doi.org/10.3390/microorganisms9010078
16. Agrawal DP, Agrawal S. Characterization of *Bacillus* sp. strains isolated from rhizosphere of tomato plants (*Lycopersicon esculentum*) for their use as potential plant growth promoting rhizobacteria. Int J Curr Microbiol App Sci. 2013;2(10):406-17.
17. Dean JR, Abdullah MP, Zakaria Z. Extraction of polycyclic aromatic hydrocarbons from contaminated soil using Soxhlet extraction, pressurized and atmospheric microwave–assisted extraction, supercritical fluid extraction and accelerated solvent extraction. Journal of Chromatography A. 1997;791(1–2):361-6. https://doi.org/10.1016/S0021–9673(97)00768–1
18. Vinci G, Cozzolino V, Mazzei P, Monda H, et al. An alternative to mineral phosphorus fertilizers: The combined effects of *Trichoderma harzianum* and compost on *Zea mays*, as revealed by 1H NMR and GC–MS metabolomics. PloS One. 2018;13(12):e0209664. https://doi.org/10.1371/journal.pone.0209664

19. Liao J, Zhang Y, Zhang W, Zeng Y, Zhao J, et al. Different software processing affects the peak picking and metabolic pathway recognition of metabolomics data. Journal of Chromatography A. 2023;1687:463700. https://doi.org/10.1016/j.chroma.2022.463700

20. BV S. A rapid procedure for the determination of available nitrogen in soils. Curr Sci. 1956;25:259-60.

21. Olsen SR. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. US Department of Agriculture. 1954.

22. Jackson ML. Soil Chemical Analysis. Prentice Hall of India Pvt. Ltd., New Delhi. 1973;200.

23. Gomez KA. Statistical procedures for agricultural research. John New York: Wiley and Sons. 1984.

24. Radzikowska–Kujawska D, Sawinska Z, Grzanka M, Kowalczewski PŁ, Sobiech Ł, Świtek S, Skrzypczak G, Drożdżyńska A, Ślachciński M, Nowicki M. *Hermetia illucens* frass improves the physiological state of basil (*Ocimum basilicum* L.) and its nutritional value under drought. PLoS One. 2023;18(1):e0280037. https://doi.org/10.1371/journal.po ne.0280037

25. Abd Manan F, Yeoh YK, Chai TT, Wong FC. Unlocking the potential of black soldier fly frass as a sustainable organic fertilizer: A review of recent studies. Journal of Environmental Management. 2024;6(367):121997. https://doi.org/10.1016/j.jenvman.2024.12199

26. Gärttling D, Schulz H. Compilation of black soldier fly frass analyses. Journal of Soil Science and Plant Nutrition. 2022:1-7. https://doi.org/10.1007/s42729–021–00703–w

27. Poveda J. Insect frass in the development of sustainable agriculture. A review. Agronomy for Sustainable Development. 2021;41(1):5. https://doi.org/10.1007/s13593–020–00656–x

28. Wang X, Wu N, Wu X, Geng W, Xu X. Effect of insect feces (*Hermetia illucens*) on rice growth and heavy metal migration from polluted soil to rice plant. Environmental Science and Pollution Research. 2022:1-0. https://doi.org/10.1007/s11356–022–18767–1

29. Green T. A biochemical analysis of Black Soldier fly (*Hermetia illucens*) larval frass plant growth promoting activity. PloS One. 2023;18(7):e0288913. https://doi.org/10.1371/journal.pone.0288913

30. Ahmad N, Kumar R, Saha T, Keerthana M, Jaiswal P. Utilizing insect frass (Faecal Matter): a sustainable approach to organic fertilization in agriculture. International Journal of Environment and Climate Change. 2024:14(4):386-96. https://doi.org/10.9734/ijecc /2024/v14i44125

31. Chirere TE, Khalil S, Lalander C. Fertiliser effect on Swiss chard of black soldier fly larvae–frass compost made from food waste and faeces. Journal of Insects as Food and Feed. 2021;7(4):457-69. https://doi.org/10.3920/JIFF2020.0120

32. Esteves C, Fareleira P, Castelo–Branco MA, Lopes IG, Mota M, Murta D, Menino R. Black soldier fly larvae frass increases the soils' residual nutrient content and enzymatic activity–a lettuce production trial. Journal of Insects as Food and Feed. 2022;8(12):1431-40. https://doi.org/10.3920/JIFF2022.0005

33. López J, Rivera S, Martínez D, Alvarado C. Sustainable agriculture using BSF frass to reduce chemical fertilizers in organic farming. Sustainable Agriculture Reviews. 2023;33(2):201-14. https://doi.org/10.1007/s11056–023–00798–2

34. Tanga CM, Beesigamukama D, Kassie M, Egonyu PJ, Ghemoh CJ, Nkoba K, Subramanian S, 13. Anyega AO, Ekesi S. Performance of black soldier fly frass fertilizer on maize (*Zea mays* L.) growth, yield, nutritional quality, and economic returns. Journal of Insects as Food and Feed. 2022;8(2):185-96. https://doi.org/10.3920/JIFF2021.0012

35. Lomonaco G, Franco A, De Smet J, Scieuzo C, Salvia R, Falabella P. Larval Frass of *Hermetia illucens* as organic fertilizer: composition and beneficial effects on different crops. Insects. 2024;15(4):293. https://doi.org/10.3390/insects15040293

36. Zhang Y, Liu X, Su R, Xiao Y, Deng H, et al, Tang W, Zhang G. 9-cis -epoxycarotenoid dioxygenase 1 confers heat stress tolerance in rice seedling plants. Frontiers in Plant Science. 20220;13:1092630. https://doi.org/10.3389/fpls.2022.1092630

37. Gamal EA, Morsy AA, Saleh HA. Changes in anatomy and phytochemistry of *Hyoscyamus muticus* L. and *Rumex vesicarius* L collected from two different sites. Acta Ecologica Sinica. 2023;43(6):1090-100. https://doi.org/10.1016/j.chnaes.2023.03.006

38. Yugandhar P, Savithramma N. Spectroscopic and chromatographic exploration of different phytochemical and mineral contents from *Syzygium alternifolim* (Wt.) Walp. an endemic, endangered medicinal tree taxon. Journal of Applied Pharmaceutical Science. 2017;7(1):073–85. https://doi.org/10.7324/JAPS.2017.70110

39. Gomathi S, Maneemegalai S. Isolation, characterization of β–sitosterol from the herbal extracts and evaluation of *in vitro* anti –oxidant and anti–diabetic activities. Journal of Microbiology, Biotechnology and Food Sciences. 2024;13(4):e10236. https://doi.org/10.55251/jmbfs.10236

40. El Gihani MT, Heaney H. The Use of Bis (trimethylsilyl) acetamide and Bis (trimethylsilyl) urea for protection and as control reagents in synthesis. Synthesis. 1998;1998(4):357-75. https://doi.org/10.1055/s–1998–2043

41. Hadi I, Hussein HM. Antimicrobial activity and spectral chemical analysis of methanolic leaves extract of *Adiantum Capillus-Veneris* using GC-MS and FT–IR spectroscopy. Int J Pharmacogn Phytochem Res. 2016;8(3):369-85.