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EVALUATION OF NUTRIENT RELEASE DYNAMICS OF SILKWORM PUPA COMPOST

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ABSTRACT

Soil fertility and nutrient management are critical factors influencing crop productivity and sustainability. Organic amendments, such as silkworm pup a compost (SPC) have gained attention for their potential to enhance soil health and nutrient availability. This study investigates the effect of SPC application on the nutrient release pattern of major nutrients through a controlled 90-day laboratory incubation study in red sandy loam soil with a neutral pH. The study aimed to assess temporal changes in soil pH, electrical conductivity (EC), organic carbon (OC), and the availability of nitrogen (N), phosphorus (P), potassium (K), and secondary nutrients following the application of SPC at 10 t/ha.

The results demonstrated a slight, but consistent decrease in soil pH over the incubation period, indicating increased microbial activity and organic acid production during the decomposition of SPC. In contrast, EC showed a gradual increase, reflecting the mineralization and release of soluble salts. SOC content significantly improved with time, contributing to better soil structure and microbial proliferation. The release of major nutrients followed a dynamic pattern, with nitrogen showing (133.46- 175.93 mg kg^{-1}) a steady increase due to the mineralization of organic matter, leading to improved nitrogen availability in the soil. Similarly, available phosphorus levels increased progressively (8.05-14.72 mg kg^{-1}), likely due to organic acid-mediated solubilization of phosphorus compounds. Available potassium also exhibited an upward trend (80.10-111.46 mg kg^{-1}), suggesting the slow release of potassium from the compost.

The study highlights the potential of SPC as an eco-friendly alternative to synthetic fertilizers by enhancing soil health and ensuring a steady nutrient supply. The observed changes in soil properties and nutrient dynamics suggest that SPC could play a significant role in sustainable soil management.

Key words : Silkworm pupa compost, Soil fertility, Nutrient mineralization, Incubation study, Sustainable soil management.

Introduction

The growing need for sustainable agricultural practices has led to the exploration of alternative organic resources to enhance soil fertility and crop productivity. Organic waste materials, particularly those derived from agro-industrial by-products, have garnered attention for their potential to improve soil health and nutrient cycling. Silkworm pupal waste, a by-product of the sericulture industry, is one such resource that holds immense potential for agricultural applications. Silkworm pupal waste is generated during the silk-reeling process and constitutes a significant portion of the by-products from silk production. It is highly enriched with nutrients, containing approximately 60-65% crude protein, along with essential minerals such as nitrogen (N), phosphorus (P) and potassium (K) (Sahoo *et al*., 2020). Additionally, it is a source of micronutrients like zinc (Zn), iron (Fe) and manganese (Mn), which are crucial for plant growth and soil health. When composted, silkworm pupal waste undergoes microbial decomposition, resulting in the production of nutrient-rich compost that can serve as an organic amendment in various cropping systems (Sujatha *et al.*, 2021).

The application of silkworm pupa (SPC) compost not only provides a slow and sustained release of major nutrients but also improves soil physio-chemical properties. It enhances soil organic carbon (SOC), increases microbial biomass, and improves soil aggregation and water-holding capacity (Ramesh *et al.*, 2018). Studies have demonstrated that integrating SPC with conventional fertilizers can optimize nutrient use efficiency while reducing dependency on chemical fertilizers.

Moreover, SPC has significant ecological benefits. Its use minimizes the environmental burden of agro-industrial waste disposal and contributes to sustainable waste management practices. By recycling nutrient-rich waste materials back into the soil, it supports the principles of circular economy and promotes environmentally friendly agricultural practices (Jayaraj *et al.*, 2019).

The nutrient-release pattern of SPC is another crucial aspect of its agronomic potential. During decomposition, the compost provides a steady supply of nutrients, particularly N, P and K, over time, ensuring their availability throughout the crop's growing season. This property is essential for maintaining soil fertility and meeting crop nutrient demands without causing nutrient leaching or other environmental issues (Sujatha *et al.*, 2021).

Despite its numerous advantages, the agronomic potential of SPC has not been fully explored. Limited research exists on its effects of SPC on soil physio-chemical properties and nutrient release patterns under different cropping systems. Therefore, the present study aims to evaluate the impact of SPC on soil health and the nutrient release dynamics of major nutrients. This study provides valuable insights into the role of SPC as a sustainable amendment for enhancing soil fertility and supporting environmentally sound agricultural practices.

Materials and Methods

An incubation study was conducted at Department of Soil Science & Agricultural Chemistry, COA, V.C Farm, Mandya, Karnataka, India to study the release pattern of available Nitrogen, Phosphorus, Potassium, Calcium, Magnesium and Sulphur from SPC (Treatment details of silkworm pupa composting is detailed in Table 2). Prior to seeding the crop, bulk soil samples for the incubation study were taken from the field experimental location. It was used for an incubation study after being air dried, finely powdered, and sieved with a 2 mm sieve. The soil was neutral in reaction, with an electrical conductivity of 0.30 dS m^{-1} and organic carbon content 0.42 %. This soil had the initial available nutrient content of 133.45 mg kg^{-1} of N, 8.24 mg kg^{-1} of P, 84.66 mg kg^{-1} of K and 12.83 mg kg^{-1} of S. The exchangeable Ca and Mg content of the soil was 6.01 and 2.07 C mol (p+) kg^{-1}.

For the conduct of incubation experiment, triplicate of 110 g of soil samples were taken in plastic cups and were mixed with SPC and FYM @ 10t/ha. The experiment was laid out in Completely Randomized Design with 7 treatments, which are replicated thrice as indicated in Table 1. Distilled water was added to maintain the moisture content at field capacity. Periodic soil samples were drawn at 15 days interval upto 90 days. The sampling for analysis of pH, EC, organic carbon, available N, P, K, Ca, Mg and S of soil was done at 0, 15, 30, 45, 60, 75 and 90 days after incubation. The nutrient content of SPC (Table 2) were determined as per standard methods *viz.*, nitrogen content was determined by micro-kjeldahl method (Piper, 1966), phosphorus, potassium, calcium and magnesium content were determined by vanadomolybdate yellow colour method, flame photometer and versenate titration method as outlined by Jackson (1973) and sulphur content was determined by turbidimetric method by Bradsley and Lancester (1965). The pH and EC of the soil was determined by potentiometric method and conductometric method, respectively given by Jackson (1973), the organic carbon content was determined by Wet oxidation method (Walkley and Black, 1934), available nitrogen was determined using the alkaline potassium permanganate method (Subbiah and Asija, 1956), available phosphorus was determined using the ammonium–molybdate–ascorbic acid method using a Spectrophotometer as outlined by Olsen *et al.* (1954) and available potassium was determined using the flame photometer method after extracting the soil with neutral normal ammonium acetate as outlined by Jackson (1973). The available Ca and Mg were determined using the versenate titration method with

Table 1 : Treatment details for mineralization study of silkworm pupa compost.

T_1	Only soil
T_2	Soil + FYM @ (10t/ha)
T_3	Soil + C1 @ (10t/ha)
T_4	Soil + C2 @ (10t/ha)
T_5	Soil + C3 @ (10t/ha)
T_6	Soil + C4 @ (10t/ha)
T_7	Soil + C5 @ (10t/ha)

Table 2 : Chemical properties of the mature insect biomass compost.

Treatments	pH	EC (dS m^{-1})	OC (dS m^{-1})	N (dS m^{-1})	C:N ratio	P (%)	K (%)	Ca (%)	Mg (%)	S (%)
C1	8.20	0.92	20.43	1.41	14.45	0.69	1.25	2.16	1.18	0.60
C2	8.10	0.95	19.64	1.48	13.27	0.79	1.37	2.21	1.23	0.68
C3	7.95	0.94	18.92	1.87	10.14	0.94	1.48	2.31	1.27	0.75
C4	8.05	0.97	19.05	1.52	12.52	0.84	1.39	2.24	1.25	0.70
C5	7.82	0.98	18.38	1.90	9.67	0.96	1.51	2.32	1.29	0.76

*C1 **-** Partially decomposed farm waste + silkworm pupae (4:1) + cow dung slurry
C2 **-** Partially decomposed farm waste + silkworm pupae (4:1) + cow dung slurry+ waste decomposer (5kg/t)
C3 **-** Partially decomposed farm waste + silkworm pupae (2:1) + cow dung slurry + waste decomposer (5kg/t)
C4 **-** Partially decomposed farm waste + silkworm pupae (4:1) + cow dung slurry + waste decomposer (10 kg/t)
C5 **-** Partially decomposed farm waste + silkworm pupae (2:1) + cow dung slurry + waste decomposer (10 kg/t).

neutral normal ammonium acetate (Jackson, 1973), while the available Sulphur was evaluated using the turbidimetric method with 0.15 $CaCl_2$ extract (Black, 1965). For correct interpretation, the data obtained for all of the traits under study were statistically analysed as proposed by Gomez and Gomez (1976). The critical difference was calculated at a 1% probability level for significant results.

Results and Discussion

Effect of silkworm pupa compost on the soil physio-chemical properties during incubation study

Soil reaction

The values depicted in Fig. 1 represents the soil reaction influenced by the application of different ratios of silkworm pupa compost. It was found that the pH of soil decreases with increase in days of incubation throughout the incubation study due to the addition of silkworm pupa compost. Initially during the incubation, soil reaction (7.40) was recorded and there was no significant difference was observed in the soil pH during the incubation period but however pH of the soil samples was decreased with increased incubation period in all the treatments.

Electrical Conductivity

The values presented in Fig. 2 indicate the effect of SPC on soil salts (EC). The data revealed that there is an increase in EC values with an increased incubation period and the highest EC values were recorded at the end of the incubation period. Initially during the incubation, electrical conductivity of the soil samples was recorded as 0.30 dS m^{-1}. However no significant differences were noticed with respect to soil EC during the incubation period.

Organic Carbon

The data with respect of organic carbon content of soil as influenced by different ratios of SPC is given in Fig. 3.

The organic carbon content increased with the increase in the incubation period, however no significant differences were noticed with respect to organic carbon content during incubation studies.

The pH of soil decreases with advancement of incubation period. This decrease in pH may be because of increasing the products of degradations of organic matter *viz.,* humic acid, fulvic acid and hymetomelonic acid. The lower pH was recorded due to T_7 treatment which might have led to formation of humic acid, carbonic acid and release of organic acids during mineralization helps to decrease soil pH. The similar observations on soil reaction were also reported by Roy and Kashem (2014). In general, the electrical conductivity of soil was found to be increased with increasing days after incubation in all the treatments during incubation study. This increase in EC of soil might be due to the mineralization of organic manures during incubation period, which serve as a measure of soluble nutrients, thus EC increases during incubation period as the mineralization of SPC increases or it may be because of after degradation and decomposition of organic manures liberates basic ions in the soil solution and subsequently adsorbed on the surface of clay minerals resulting in increase in EC of soil. The similar observations on soil EC in present study were also reported earlier by Roy and Kashem (2014).

The highest organic carbon content at the end might be due to availability of larger pool of the less resistant fractions that were available to be broken down and recycled, thus resulting in lower contents remaining at the end of incubation period. Initially, the increase in OC content of soil may be attributed to the increase in the most probable numbers of micro fauna, which might be release CO_2. It may also be attributed to decomposition of dissolved native humic substances and readily available

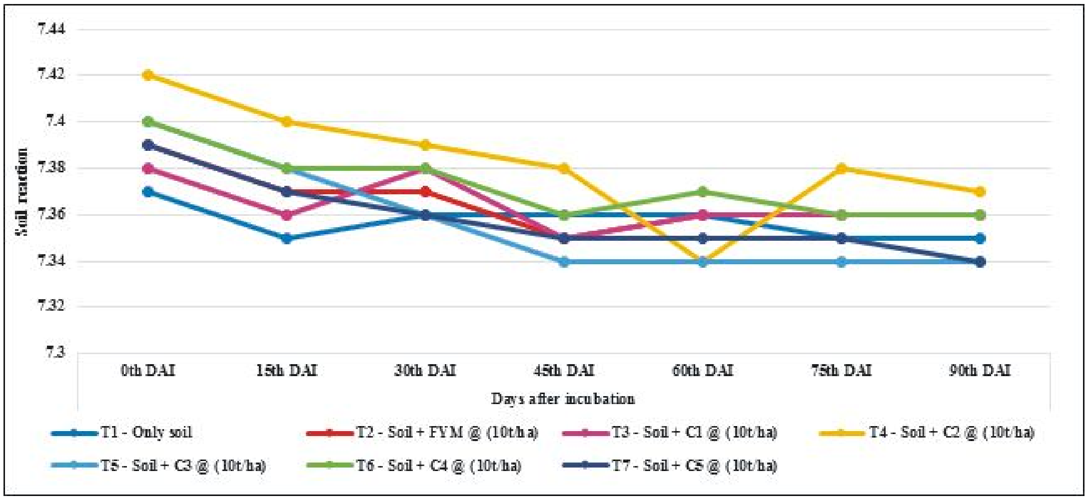

Fig. 1 : Effect of silkworm pupa compost on soil reaction during incubation study.

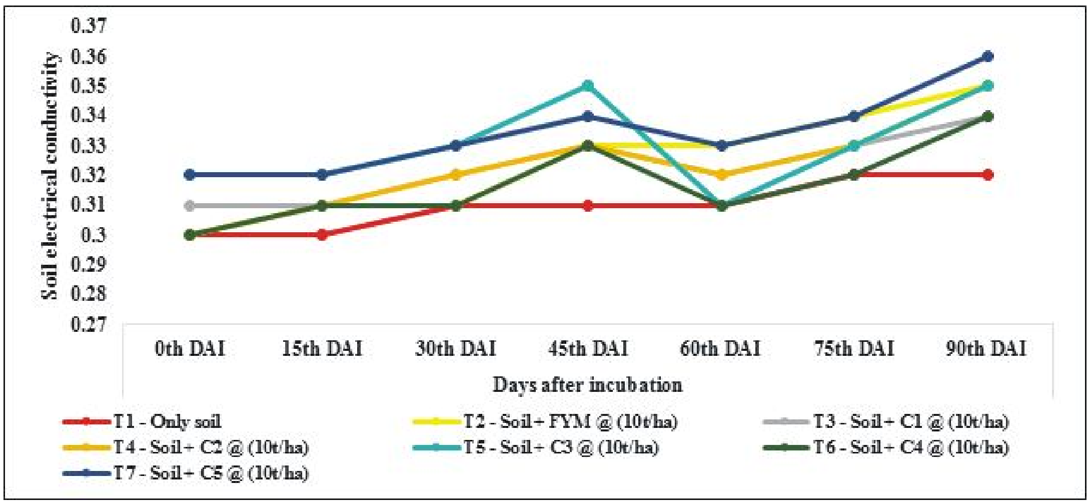

Fig. 2 : Effect of silkworm pupa compost on soil electrical conductivity (dSm^{-1}) during incubation study.

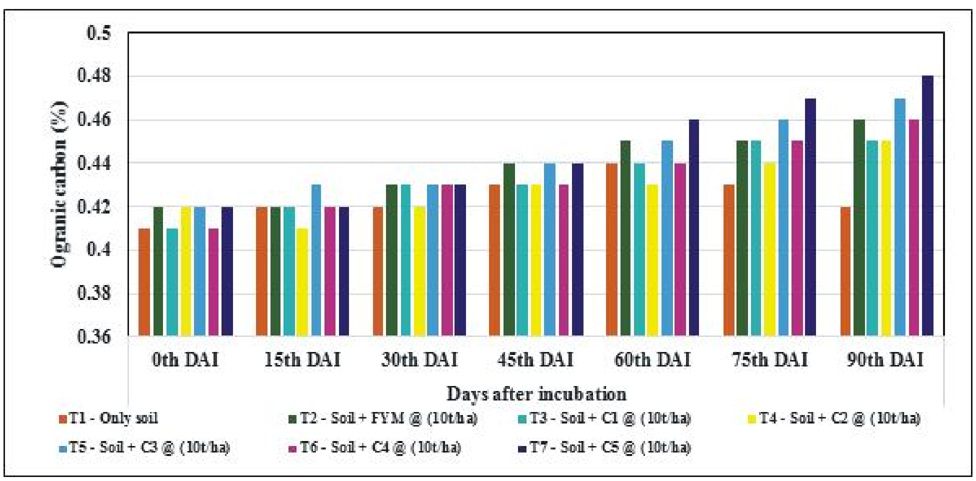

Fig. 3 : Effect of silkworm pupa compost on soil organic carbon during incubation study.

water-soluble organic fractions and also due to rapid decomposition of readily water-soluble constituents of added organic matter. The above observations are close in agreement with the observations of Roy and Kashem (2014) and Follet *et al*. (2007).

Effect of silkworm pupa compost on the release pattern of primary nutrients during incubation study

The effect of SPC on primary nutrient mineralization was observed on 0^{th}, 15^{th}, 30^{th}, 45^{th}, 60^{th}, 75^{th} and 90^{th} days after incubation in Table 3 and Fig. 3.

Table 3 : Effect of silkworm pupa compost on available nitrogen and phosphorous (mg kg^{-1}) of soil during incubation study.

Weeks of incubation/ treatments	Available nitrogen (mg kg^{-1})							Available phosphorous (mg kg^{-1})						
	0th DAI	15th DAI	30th DAI	45th DAI	60th DAI	75th DAI	90th DAI	0th DAI	15th DAI	30th DAI	45th DAI	60th DAI	75th DAI	90th DAI
T_1	133.46	134.63	136.03	136.33	136.95	136.35	135.97	8.05	8.05	8.05	8.05	8.11	8.25	8.38
T_2	134.76	136.93	139.26	140.36	146.15	150.36	153.21	8.07	8.56	9.15	9.55	10.05	10.18	10.57
T_3	134.93	140.29	142.96	143.85	149.64	155.63	158.80	8.06	8.91	9.64	9.86	11.40	11.83	12.02
T_4	135.08	142.52	143.85	145.96	151.75	159.59	162.76	8.07	9.00	9.75	10.16	12.07	12.93	13.36
T_5	136.17	145.03	150.88	154.75	158.54	168.67	170.84	8.08	9.45	10.56	11.94	13.52	13.76	14.16
T_6	135.73	143.06	145.72	148.39	154.18	162.52	166.03	8.07	9.21	9.81	10.56	12.39	13.32	13.90
T_7	136.37	147.22	152.32	156.00	163.79	171.75	175.93	8.08	9.54	10.80	12.00	13.89	14.22	14.72
SEm ±	0.79	0.91	1.38	2.05	2.79	2.71	2.78	0.40	0.40	0.23	0.33	0.33	0.20	0.14
CD @ 1%	NS	2.80	5.96	8.87	8.53	8.34	8.56	NS	NS	0.98	1.43	1.43	0.88	0.59

Available nitrogen

Initially during the incubation, the available N content was observed as 131.6 mg kg^{-1} in soil samples collected. The available nitrogen content of all the treatments due to application of various SPC varied between 133.46 to 175.93 mg kg^{-1} over control (133.46 to 135.97 mg kg^{-1}). The maximum increased available nitrogen was observed on 90th days after incubation. Among all the treatments, T_7 which received soil + C5 @ (10 t/ha) recorded significantly the highest available nitrogen at 15th, 30th, 45th, 60th, 75th and 90th DAI (147.22, 152.32, 156.00, 163.79, 171.75, and 175.93 mg kg^{-1}, respectively) and which was statistically at par with treatment T_5 which received soil + C3 @ 10t/ha (145.03, 150.88, 154.75, 158.54, 168.67 and 170.84 mg kg^{-1}, respectively) as compared to control (134.63, 136.03, 136.33, 136.95, 136.35 and 135.97 mg kg^{-1}, respectively) as depicted in Table 3.

The treatment T_7 and T_5 was followed by T_6 which received soil+ C4 @ 10t/ha (143.06, 145.72, 148.39, 154.18, 162.52 and 166.03 mg kg^{-1}, respectively on 15, 30, 45, 60, 75 and 90 DAI), T_4 which received soil + C2 @ 10t/ha (142.52, 143.85, 145.96, 151.75, 159.59 and 162.76 mg kg^{-1}, respectively on 15, 30, 45, 60, 75 and 90 DAI), and T_3 which received soil+ C1 @ 10t/ha (140.29, 142.96, 143.85, 149.64, 155.63 and 158.80 mg kg^{-1}, respectively on 15, 30, 45, 60, 75 and 90 DAI).

Silkworm pupae are known to contain significant amounts of protein, which translates to elevated nitrogen levels in compost made from them. Upon application, the compost undergoes microbial decomposition, leading to the mineralization of organic nitrogen into inorganic forms such as ammonium (NH_4^+) and nitrate (NO_3^-). This conversion process is accelerated by microbial activity, which increases as microorganisms utilize the organic material from the compost as a nutrient source. The presence of high-quality organic matter from silkworm pupae also enhances the soil's microbial biomass, fostering an environment conducive to sustained mineralization. Consequently, nitrogen is gradually released in a plant-available form, making it accessible for uptake over the incubation period (Chatterjee *et al.*, 2015; Ahmad *et al.*, 2019).

In addition to nitrogen mineralization, SPC enhances soil structure and organic matter content, which are key factors in nitrogen retention and availability. As the compost decomposes, organic matter levels in the soil increase, improving its moisture-holding capacity and cation exchange capacity (CEC). These properties allow the soil to retain more nutrients, including nitrogen, reducing losses through leaching and volatilization. This synergistic effect of nutrient-rich organic amendments and improved soil physical properties promotes a stable supply of available nitrogen over time, which can enhance the soil's fertility and potential crop productivity. Studies have shown that organic amendments like SPC not only supply nutrients directly but also contribute to a more resilient nutrient cycle within the soil ecosystem, thereby ensuring a sustained increase in nitrogen availability (Singh *et al.*, 2018; Pathak and Rao, 2019). Earlier Roy and Kashem (2014) also reported similar pattern of NH_4-N release from cow dung and poultry manure. Similar pattern of NH_4-N release from urban compost and poultry manure was found by El-Ghamry *et al*. (2015). The similar results with respect to available nitrogen were also reported by Gupta *et al*. (2020) and Yu *et al*. (2014).

Available phosphorous

As observed in Table 3, significant differences were noticed with respect to available phosphorous content of soil during incubation of 30th day onwards. Significantly lower mineralization was noticed in the control treatment during different incubation days (8.05, 8.05, 8.11, 8.25

and 8.38 mg kg^{-1} on 30, 45, 60, 75 and 90 DAI, respectively) and in T_2 treatment which received soil + FYM @ 10t/ha showed 9.15, 9.55, 10.05, 10.18 and 10.57 mg kg^{-1} on 30, 45, 60, 75 and 90 DAI, respectively.

Significantly higher phosphorous mineralization was noticed in T_7 (Soil + C5 @ 10t/ha) with the values of the 10.80, 12.00, 13.89, 14.22 and 14.72 mg kg^{-1} on 30, 45, 60, 75 and 90 DAI, respectively and it found statistically on par with T_5 (soil + C3 @ 10t/ha) with the values of 10.56, 11.94, 13.52, 13.76 and 14.16 mg kg^{-1} on 30, 45, 60, 75 and 90 DAI, respectively. Further, was followed by T_6 which received soil + C4 @ 10t/ha (9.81, 10.56, 12.39, 13.32 and 13.90 mg kg^{-1} on 30, 45, 60, 75 and 90 DAI, respectively), T_4 which received soil + C2 @ 10t/ha (9.75, 10.16, 12.07, 12.93 and 13.36 mg kg^{-1} on 30, 45, 60, 75 and 90 DAI, respectively) and T_3 which received soil + C1 @ 10t/ha (9.64, 9.86, 11.40, 11.83 and 12.02 mg kg^{-1} on 30, 45, 60, 75 and 90 DAI, respectively).

The increase in available phosphorus content in soil during an incubation study is largely attributed to the phosphorus content and organic compounds such as humic and fulvic acids in the compost. SPC not only supplies phosphorus directly but also includes humic substances like humic and fulvic acids that play a key role in phosphorus availability. These acids contain functional groups like carboxyl (-COOH) and hydroxyl (-OH) that can chelate soil minerals, aiding in the release of phosphorus bound to soil particles. Humic and fulvic acids enhance phosphorus solubility by complexing with calcium, iron, and aluminum ions, which typically immobilize phosphorus in unavailable forms. By binding with these ions, the humic substances in the compost prevent phosphorus fixation, keeping it in a form accessible to plants. Kumar *et al*. (2017) and Singh *et al*. (2018) found that organic acids improve soil microbial activity, which further enhances phosphorus mineralization from organic matter. Studies have demonstrated that organic amendments rich in humic and fulvic acids significantly increase the availability of phosphorus in soils, improving nutrient cycling and soil fertility over time. The similar results on soil available P were also reported by Bihari *et al*. (2018), Yu *et al*. (2014) and Shrinivasan *et al*. (2016).

Available potassium

Significantly higher potassium mineralization was noticed due to implementation T_7 (soil + C5 @ 10t/ha) and it was followed by T_6 (soil+ C4 @ 10t/ha) with the values of 80.27, 87.29, 92.36, 96.03, 98.88, 101.36 and 104.29 mg kg^{-1} on 0th, 15th, 30th, 45th, 60th, 75th and 90th DAI, respectively, T_4 (soil+ C2 @ 10t/ha) with the values of 80.26, 85.03, 90.55, 94.10, 97.43, 100.26 and 102.56 mg kg^{-1} on 0th, 15th, 30th, 45th, 60th, 75th and 90th DAI, respectively and T_3 which received soil + C1 @ 10t/ha with the values 80.29, 83.03, 89.70, 91.67, 96.33, 98.67 and 100.00 mg kg^{-1} on 0th, 15th, 30th, 45th, 60th, 75th and 90th DAI, respectively.

Significantly higher potassium mineralization was noticed by T_7 (soil + C5 @ 10t/ha) with the values of the 80.96, 90.19, 96.19, 101.06, 103.63, 106.71 and 111.46 mg kg^{-1} on 0th, 15th, 30th, 45th, 60th, 75th and 90th DAI, respectively and it was found statistically on par with T_5 (soil + C3 @ 10t/ha) with the values of 80.52, 88.73, 93.06, 98.88, 101.36, 103.46 and 107.37 mg kg^{-1} on 0th, 15th, 30th, 45th, 60th, 75th and 90th DAI, respectively.

SPC contains significant potassium, which, as it decomposes, is released into the soil in a form accessible to plants. Humic substances, such as humic and fulvic acids in the compost, play a crucial role in this process by enhancing potassium availability through their functional groups, including carboxyl (-COOH) and hydroxyl (-OH). These functional groups interact with soil minerals, affecting the soil's cation exchange capacity (CEC) and allowing for greater retention of potassium ions in the soil solution. This CEC enhancement prevents potassium leaching and makes it readily available for plant uptake, while also contributing to improved soil structure and nutrient-holding capacity (Khan *et al*., 2018; Prasad *et al*., 2020). The similar results on soil available K were also reported by Gupta *et al*. (2020), Shrinivasan *et al*. (2016) and Elnour *et al*. (2018).

Effect of silkworm pupa compost on the release pattern of secondary nutrients during incubation study

The secondary nutrient mineralization pattern in soil amended with different ratios of SPC is presented in Table 5. The effect of SPC on secondary nutrient mineralization was observed at 0th, 15th, 30th, 60th, 75th and 90th days of incubation.

Exchangeable calcium and magnesium

Initially during the incubation, the exchangeable calcium content was observed as 6.01 cmol (p^+) kg in soil samples collected. The exchangeable calcium content of all the treatments due to application of various SPC varied from 6.03 - 7.56 cmol (p^+) kg. The maximum increased exchangeable calcium was observed on 90th days after incubation. Among all the treatments, T_7 which received soil + C5 @ (10t/ha) recorded significantly the highest available calcium at 15th, 30th, 45th, 60th, 75th and 90th DAI (6.32, 6.78, 7.04, 7.21, 7.35 and 7.56 cmol (p^+) kg, respectively) and which was statistically at par with treatment T_5 which received soil + C3 @ 10t/ha (6.25,

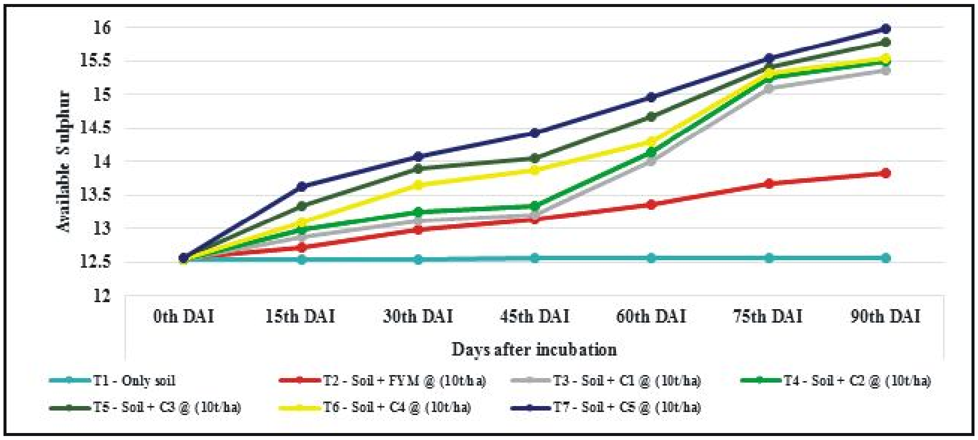

Fig. 4 : Effect of silkworm pupa compost on available sulphur (mg kg^{-1}) of soil during incubation study.

6.65, 6.85, 7.02, 7.23 and 7.37 cmol (p^+) kg, respectively) as compared to control (6.01, 6.02, 6.03, 6.03, 6.03 and 6.03 (cmol (p^+) kg), respectively).

Significantly higher exchangeable magnesium was noticed in T_7 (Soil + C5 @ 10t/ha) with the values of the 2.75, 2.95, 3.06, 3.19 and 3.38 (cmol (p^+) kg) on 30, 45, 60, 75 and 90 DAI, respectively and it was statistically on par with T_5 (soil + C3 @ 10t/ha) with the values of 2.64, 2.81, 2.93, 3.09 and 3.30 (cmol (p^+) kg) on 30, 45, 60, 75 and 90 DAI, respectively and it was followed by T_6, which received soil + C4 @ 10t/ha (2.53, 2.75, 2.88, 3.03 and 3.16 (cmol (p^+) kg) on 30, 45, 60, 75 and 90 DAI, respectively), T_4 which received soil + C2 @ 10t/ha (2.42, 2.70, 2.82, 2.97 and 3.11 (cmol (p^+) kg) on 30, 45, 60, 75 and 90 DAI, respectively) and T_3 which received soil + C1 @ 10t/ha (2.39, 2.67, 2.87, 2.93 and 3.05 (cmol (p^+) kg) on 30, 45, 60, 75 and 90 DAI, respectively).

Silkworm pupae contains a substantial amount of calcium carbonate within their exoskeletons, providing a readily available source of calcium upon decomposition. When applied to the soil, the organic matter in SPC undergoes microbial breakdown, during which calcium ions (Ca^{2+}) are released into the soil in an exchangeable form that plants can absorb. This process is facilitated by soil microbial activity, which not only aids in decomposing the organic material but also enhances the mineralization of calcium, thereby increasing its availability in the soil environment (Li *et al.*, 2019). In addition to the direct contribution of calcium from the pupal shells, humic substances within the compost, such as humic and fulvic acids, play a vital role in retaining calcium in the soil. Similar results were noticed by Mukherjee *et al*. (2020).

Silkworm pupae are known to contain essential minerals, including magnesium, which becomes available in the soil as the compost decomposes. During microbial breakdown of the compost, magnesium ions (Mg^{2+}) are released, becoming part of the soil's exchangeable nutrient pool, readily accessible for plant uptake. The steady mineralization of magnesium from SPC enriches the soil with this essential nutrient, increasing its availability over time. Research shows that organic amendments derived from nutrient-rich sources like insect biomass can significantly improve soil magnesium content, supporting crop nutrition and soil health (Ramesh *et al*., 2018; Chen *et al*., 2020).

Available sulphur

Significantly higher sulphur mineralization was noticed in T_7 (soil + C5 @ 10t/ha) and it was followed by T_6 (soil+ C4 @ 10t/ha) and the values of 12.55, 13.09, 13.66, 13.87, 14.29, 15.32 and 15.53 mg kg^{-1} on 0^{th}, 15^{th}, 30^{th}, 45^{th}, 60^{th}, 75^{th} and 90^{th} DAI, respectively (Fig. 4).

Significantly higher sulphur mineralization was noticed due to T_7 (soil + C5 @ 10t/ha) with the values of the 12.57, 13.64, 14.07, 14.43, 14.96, 15.53 and 15.99 mg kg^{-1} 0^{th}, 15^{th}, 30^{th}, 45^{th}, 60^{th}, 75^{th} and 90^{th} DAI, respectively and it was statistically on par with T_5 (soil + C3 @ 10t/ha) with the values of 12.56, 13.35, 13.89, 14.05, 14.67, 15.40 and 15.78 mg kg^{-1} 0^{th}, 15^{th}, 30^{th}, 45^{th}, 60^{th}, 75^{th} and 90^{th} DAI, respectively. Similarly, statistically lower mineralization was noticed in control treatment *i.e.*, (12.55, 12.55, 12.55, 12.56, 12.56, 12.56 and 12.57 mg kg^{-1} on 0^{th}, 15^{th}, 30^{th}, 45^{th}, 60^{th}, 75^{th} and 90^{th} DAI, respectively).

Silkworm pupae contain sulfur-rich amino acids and proteins, which, when added to the soil as compost, gradually decompose through microbial activity. As microorganisms break down these organic sulfur compounds, they release sulfate (SO_4^{2-}) ions- a form of sulfur readily available for plant uptake. This microbial-driven mineralization process converts the organically bound sulfur in the pupae into an inorganic, plant-accessible form, steadily increasing sulfur availability in the soil over the incubation period. Furthermore, the organic matter in the compost enhances microbial

Table 4 : Effect of silkworm pupa compost on available potassium (mg kg^{-1}) of soil during incubation study.

Weeks of incubation/ treatments	Available potassium (mg kg^{-1})						
	0^{th} DAI	15^{th} DAI	30^{th} DAI	45^{th} DAI	60^{th} DAI	75^{th} DAI	90^{th} DAI
T_1 - Only soil	80.10	80.17	80.43	80.43	80.60	81.67	81.83
T_2 - Soil + FYM @ (10t/ha)	80.11	81.71	84.38	89.38	93.71	95.74	98.07
T_3 - Soil + C1 @ (10t/ha)	80.29	83.03	89.70	91.67	96.33	98.67	100.00
T_4 - Soil + C2 @ (10t/ha)	80.26	85.03	90.55	94.10	97.43	100.26	102.56
T_5 - Soil + C3 @ (10t/ha)	80.52	88.73	93.06	98.88	101.36	103.46	107.37
T_6 - Soil + C4 @ (10t/ha)	80.27	87.29	92.36	96.03	98.88	101.36	104.29
T_7 - Soil + C5 @ (10t/ha)	80.96	90.19	96.19	101.06	103.63	106.71	111.46
SEm±	0.54	0.91	1.15	1.56	1.53	1.59	2.78
CD@1%	NS	2.80	3.55	4.81	4.70	4.91	8.57

Table 5 : Effect of silkworm pupa compost on exchangeable calcium and magnesium (cmol (p^+) kg) of soil during incubation study.

Weeks of incubation/ treatments	Exchangeable calcium (cmol (p^+) kg)							Exchangeable magnesium (cmol (p^+) kg)						
	0^{th} DAI	15^{th} DAI	30^{th} DAI	45^{th} DAI	60^{th} DAI	75^{th} DAI	90^{th} DAI	0^{th} DAI	15^{th} DAI	30^{th} DAI	45^{th} DAI	60^{th} DAI	75^{th} DAI	90^{th} DAI
T_1	6.01	6.01	6.02	6.03	6.03	6.03	6.03	2.12	2.12	2.12	2.13	2.13	2.13	2.14
T_2	6.01	6.08	6.30	6.42	6.48	6.56	6.68	2.13	2.15	2.27	2.55	2.80	2.85	2.90
T_3	6.03	6.09	6.50	6.68	6.83	6.90	6.97	2.13	2.18	2.39	2.67	2.87	2.93	3.05
T_4	6.00	6.10	6.52	6.79	6.91	7.01	7.11	2.12	2.22	2.42	2.7	2.82	2.97	3.11
T_5	6.04	6.25	6.65	6.85	7.02	7.23	7.37	2.14	2.43	2.64	2.81	2.93	3.09	3.30
T_6	6.02	6.21	6.56	6.82	6.95	7.05	7.17	2.12	2.31	2.53	2.75	2.88	3.03	3.16
T_7	6.03	6.32	6.78	7.04	7.21	7.35	7.56	2.14	2.54	2.75	2.95	3.06	3.19	3.38
SEm±	0.45	0.41	0.05	0.06	0.08	0.095	0.12	0.01	0.01	0.03	0.04	0.03	0.03	0.05
CD @ 1%	NS	NS	0.17	0.21	0.25	0.30	0.36	NS	NS	0.12	0.15	0.15	0.15	0.22

biomass, which can boost the rate of sulfur mineralization and ensure a continuous supply of sulfur. Studies by Patra *et al*. (2018), Singh and Aulakh (2020) have shown that organic amendments derived from insect biomass, such as silkworm pupae, not only improve soil nutrient levels but also support sustainable sulfur cycling in soils, which is beneficial for sulfur-demanding crops.

Conclusion

The 90-day laboratory incubation study demonstrated that silkworm pupa compost (SPC) significantly influences soil physico-chemical properties and nutrient release dynamics in red sandy loam soil. SWPC application led to a slight decrease in soil pH, an increase in electrical conductivity, and enhanced soil organic carbon content. The gradual and sustained release of nitrogen, phosphorus, and potassium, along with increased secondary nutrients indicates improved soil fertility. These findings highlight SPC as a promising organic amendment for sustainable nutrient management. Further research is recommended to assess its long-term effects and potential benefits under field conditions.

Declaration

The authors declare no conflict of interest.

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