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INNOVATIVE APPROACHES TO OPTIMIZE TEA WASTE FOR SUSTAINABLE PRODUCT DEVELOPMENT

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ABSTRACT

The tea industry, crucial for many economies, faces significant waste challenges from agricultural fields and processing facilities. This study introduces an innovative, eco-friendly approach to mitigate tea waste through composting, transforming it into valuable products that bolster sustainable agriculture and support carbon neutrality goals. This approach, which emphasises the creation of compost, biodegradable mulching sheets and tea peat from tea waste, offers alternatives to plastic mulch and coco-peat, enhancing weed suppression, soil moisture retention, and soil health. Detailed analyses encompassed the compost's nutrient content, pH levels, moisture content, and derivatives. Tea peat exhibited exceptional water retention capabilities, suggesting its potential to optimise soil moisture management. This study underscores the advantages of converting tea waste into beneficial products, promoting sustainable waste management and advancing agricultural practices towards carbon neutrality. By reducing dependency on synthetic inputs, this research highlights the dual benefits of waste valorisation and environmental sustainability in the tea industry, instilling hope for a more sustainable future.

***Keywords*:** Tea waste management, composting, biodegradable mulching sheets, tea peat, carbon neutrality

Introduction

In recent decades, there has been a notable surge in the generation of solid wastes worldwide, primarily attributed to population growth and accelerated by modern lifestyles and urbanisation (Karak *et al.*, 2012; Hoornweg & Bhada-Tata, 2012; Zaman & Lehmann, 2013; Gupta *et al.*, 2015). Estimates suggest that approximately 2 billion tons of solid waste were generated in cities globally during 2016 (Kaza *et al.*, 2018; World Bank, 2019), exerting significant pressure on environmental systems. To address this challenge, there is an urgent need for appropriate and environmentally friendly solid waste management strategies (Troschinetz & Mihelcic, 2009; Guerrero *et al.*, 2013; Singh & Ordoñez, 2016). Among these strategies, the reuse and recycling of organic wastes are considered crucial components of integrated solid waste management systems within the framework of a circular economy.

Tea production is a worldwide cornerstone of agricultural economies, yielding substantial waste materials, mainly from tea fields and factories. These by-products, pruning litter including tea leaves, stems, and factory waste, pose significant environmental challenges if not managed effectively. However, with increasing awareness of sustainability and circular economy principles, researchers and industries are exploring innovative approaches to valorise tea waste and minimise its environmental footprint. Composting is a promising strategy for managing tea waste, including factory tea waste. Composting offers a sustainable solution for waste reduction and producing nutrient-rich compost, enhancing soil fertility and promoting plant growth. Understanding the composting process dynamics over time is crucial for optimising nutrient release and compost quality. Thus, investigations at different time points of composting, such as 1st, 2nd, 3rd, and 4th months, are essential for comprehensively assessing the effectiveness of composting strategies. In addition to composting, developing diversified products from tea waste holds immense potential. Furthermore, preparing tea peat and mulching sheets from tea waste presents an innovative solution for enhancing soil health and moisture retention in tea fields. Tea peat, rich in organic matter and nutrients, is an excellent soil conditioner, improving soil structure and promoting microbial activity (Sultana *et al.*, 2015; Yadav *et al.*, 2017; Hazarika *et al.*, 2019). Mulching sheets made from tea waste fibres offer sustainable weed suppression and moisture conservation solutions, reducing the need for herbicides and irrigation in tea cultivation. Compost is characterised by its high organic matter content and abundance of macro- and micronutrients, resulting in positive effects on soil biological and physicochemical properties (Bernal *et al.*, 2009; Ogunwande *et al.*, 2008; Rigby & Smith, 2011). Its widespread use as an alternative to inorganic fertilizers has led to significant savings in fertiliser costs without compromising crop yields. (Khalid *et al.*, 2016; Cobo *et al.*, 2010; Bationo *et al.*, 2012).

This research paper explores the potential of tea waste valorisation through composting, production of tea peat and mulching sheet using natural adhesive. By integrating scientific insights and practical applications, this study seeks to contribute significantly to sustainable waste management practices in the tea industry and promote adopting eco-friendly solutions. This research also aims to provide insights into the composting process as a method for treating organic waste, detailing the characteristics of the final product and its applications in agriculture. Additionally, it underscores the importance of composting in advancing agricultural sustainability and soil fertility restoration, highlighting the significance of the work in shaping a more sustainable future.

Materials and Methods

Composting of tea waste

Composting is an alternative for solid waste management, reducing environmental pollution and recovering nutrient resources. It converts organic matter into high-quality compost through biochemical and biological actions. Temperature, oxygen, moisture, porosity, and C/N ratio are important parameters for process control. Tea waste from fields and factories was composted. The method involved the following steps:

Pruning litter and factory tea waste were collected. The pruning litter was shredded to small particle size to accelerate composting. The tea waste was then placed under two different conditions for decomposition. One batch was placed in a controlled laboratory environment (usually around 20-25°C, while the other was placed in a greenhouse (25-30°C).

Water was added to the shredded pruning litter till damp and carefully placed in compost pots. A damp towel covered the mixture, ensuring optimal moisture levels. Over time, the compost was diligently turned to maintain optimal aeration throughout the pots and closely monitored to maintain appropriate temperature and moisture content, promoting the breakdown of organic matter into nutrient-rich compost. After a thorough four month composting process, the organic matter matured into a stable, nutrient-rich product. The degradation of compost material after 1st, 2nd, 3rd, 4th month of composting is depicted in Table 1.

Development of Biodegradable Mulching Sheets

Organic waste materials, including tea factory and field waste, were meticulously mixed with natural glue (Table 2) and water in precisely measured proportions to create a consistent and uniform mixture. This blend was carefully prepared to achieve the desired consistency for sheet formation, ensuring suitability for its intended purpose. The mixture was then cast into sheets of manageable size of 55 cm length, 40 cm breadth and 1.4 cm thickness. Following casting, the sheets underwent a pressing process to remove excess water and compact the material, enhancing their durability. The pressed sheets were sundried or oven dried to reduce moisture to a final moisture content of 12-16%, ensuring uniform dryness.

Development of Tea Peat

Tea wastes were shredded to a fine texture for tea peat production. Shredded matter was sieved to remove large particles, ensuring a uniform and fine consistency suitable for soil amendment. The organic material was mixed with binding agent (water and flour) and compacted into small, loose peat, with the degree of compaction adjusted based on its intended use (Table 3). This process ensures that the peat maintains an optimal structure and density for its specific application, whether for soil conditioning, as a growing medium, or for other agricultural or horticultural purposes.

Nutrient Content Analysis of Tea Waste Products

The nutrient content of the composted tea waste, biodegradable mulching sheets, and tea peat was analysed using standard laboratory methods. Samples were collected, air-dried, ground, and then subjected to various analyses. Methods were adapted from "Methods of Soil Analysis: Part 3-Chemical Methods" and "Soil Chemical Analysis" by M.L. Jackson. The data were statistically analysed using mean and standard deviation to interpret the nutrient content of the compost, mulching sheets, and tea peat.

Macronutrient Analysis

The nitrogen (N) content was determined using the Kjeldahl method. Approximately 0.5 grams of the dried sample were initially digested with concentrated sulfuric acid (H_2SO_4) in the presence of a catalyst, typically a mixture of selenium, copper sulphate, and potassium sulphate. Following digestion, the sample was neutralised with sodium hydroxide (NaOH) and distilled to release ammonia, which was then collected in a boric acid solution. Finally, the ammonia was titrated with standard sulfuric acid to ascertain the nitrogen content.

The phosphorus (P) content was determined using the vanado-molybdate yellow color. In this process, 0.5 grams of the sample were digested with a mixture of nitric acid (HNO_3) and perchloric acid ($HClO_4$). The digested sample was then reacted with ammonium molybdate and vanadium chloride to form a yellow complex. The intensity of the yellow colour was measured at 420 nm using a UV-Vis spectrophotometer. For potassium (K) content, 1 gram of the sample was extracted with an ammonium acetate (NH_4OAc) solution. The potassium content in the extract was measured using a flame photometer, which was calibrated with standard potassium solutions to ensure accurate readings. Calcium and magnesium were quantified using atomic absorption spectrophotometry (AAS) (Table 4).

Micronutrient Analysis

Micronutrient analysis for iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu) was conducted using Atomic Absorption Spectrophotometry (AAS). The process began with digestion, where 0.5 grams of the sample were treated with a mixture of nitric acid (HNO_3) and hydrogen peroxide (H_2O_2) to break down the sample and release the micronutrients into a solution. Following digestion, the concentrations of the micronutrients Fe, Mn, Zn, and Cu were determined using AAS. The spectrophotometer was calibrated with appropriate standards for each element to ensure accurate measurement. This method provides precise quantification of each micronutrient, which is essential for evaluating the nutrient profile of the sample (Table 6).

Moisture Content and pH

Gravimetric Method and pH meter was used to determine the moisture content and pH, respectively.

Water Absorption Capacity of Tea Peat

The water absorption capacity of tea peat was assessed to evaluate its effectiveness in retaining moisture in soil. Initially, the dry weight of the tea peat was recorded as 850 grams. The tea peat was then submerged in 2 litres of water for 5-6 hours.

Results and Discussion

Composting Process of Tea Waste

The composting process for tea waste from fields and factories was closely monitored for 4 months (0-120 days), i.e., the time taken for compost maturation. The process involved regular turning, moisture control, and temperature monitoring to ensure optimal decomposition and nutrient stabilisation. The composting process results are discussed in terms of temperature progression, moisture content, and the final quality of the compost.

The temperature and microbial activity go through distinct phases during the composting process. In the Mesophilic Phase (0-5 days), the temperature gradually increased to around 40°C due to the activity of mesophilic microorganisms that began decomposing the readily degradable organic matter. The Thermophilic Phase (5-45 days) followed, marked by a sharp rise in temperature, peaking at approximately 65°C. This high-temperature phase, driven by thermophilic microorganisms, is essential for rapidly breaking down complex organic materials and eliminating pathogens and weed seeds (Smith & Brown, 2020). Regular turning during this phase ensured even temperature distribution and proper aeration, preventing anaerobic conditions. Finally, the temperature gradually decreased to ambient levels in the Cooling/Maturation Phase (45-90 and 90-120 days). This phase allowed for the stabilisation and maturation of the compost, during which slower microbial activity continued to break down more resistant organic matter (Figure 1).

The temperature changes observed are consistent with the findings of Bernal *et al.* (2009), who emphasised the importance of the thermophilic phase in pathogen destruction and organic matter stabilisation. Temperature management through regular turning was critical to achieving a homogeneous composting process and ensuring the quality of the final product.

Moisture Content

Maintaining optimal moisture content (50-60%) was essential throughout composting to support microbial activity and facilitate decomposition. Regular monitoring and adjustment ensured that the moisture levels remained within this range. Adequate moisture promotes efficient microbial activity, preventing the pile from becoming anaerobic or excessively dry (Lee & Kim, 2021). The moisture content of the composting material was monitored regularly, with adjustments made as necessary by adding water or turning the pile to enhance aeration and moisture distribution. The final moisture content of the compost was 42%, (Table 4) which is within the ideal range for mature compost, facilitating its application and storage (Haug, 1993; Smith, 2013; Fukumoto & Kato, 2008).

Final Quality of Compost

At the end of the 90–120-day composting period, the tea waste had fully decomposed into dark, crumbly, and earthy-smelling compost. The final quality of the compost was assessed based on its physical characteristics, nutrient content, pH, and moisture content.

Nutrient Content: The compost was found to be rich in essential nutrients, including nitrogen (N), phosphorus (P), and potassium (K). Specifically, the nitrogen content was 1.83%, phosphorus content was 0.78%, and potassium content was 1.24% (Table 5). These nutrient levels indicate that the compost can be an effective soil amendment, providing essential nutrients for plant growth (Smith & Brown, 2020). The nutrient content analysis aligns with the findings of Hargreaves *et al*. (2008), who highlighted the significant nutrient contributions of compost to soil fertility. The high nitrogen content, in particular, underscores the compost's potential to enhance plant growth and productivity.

pH: The pH of the final compost ranged from slightly acidic to neutral (6.5-7.0), which is optimal for most crops and enhances nutrient availability (Table 4). This pH range is beneficial for maintaining soil health and promoting plant growth (Wang & Chen, 2019).The pH stability observed in the final compost is consistent with the work of Bernal *et al*. (2009), who reported that well-managed composting processes typically result in neutral to slightly acidic final products. This pH range is conducive to the availability of most plant nutrients.

Water Absorption Capacity of Tea Peat

The wet weight of soaked tea peat was measured and recorded as 1.4 kg. The remaining water in the bucket was measured at 700 ml, indicating that the tea peat had absorbed 1.3 litres of water from the initial 2 litres. The water absorption capacity based on weight difference was calculated to be 64.7%, and the volume-based calculation showed that the tea peat absorbed approximately 1.53 ml of water per gram of its dry weight. This measurement demonstrated the tea peat's capacity to retain moisture effectively. The high-water retention capacity of the tea peat is consistent with the findings of Wang & Chen (2019), who reported that organic soil conditioners significantly enhance soil moisture retention.

Conclusion

Composting tea waste from fields and factories is an effective strategy for sustainable waste management and agricultural improvement. Over a period of 90-120 days, tea waste is transformed into nutrient-rich compost and other products like biodegradable mulching sheets, and tea peat. The process not only breaks down organic matter and eliminates pathogens but also produces compost rich in essential nutrients, nitrogen (1.83%), phosphorus (0.78%), and potassium (1.24%), that enhance soil fertility and support plant growth, reducing the need for synthetic fertilisers. In addition to compost, biodegradable mulching sheets and tea peat offer significant benefits. The mulching sheets has potential as a natural weed suppressant and gradually release nutrients into the soil, while tea peat shows excellent water retention capacity, contributing to soil health and reducing irrigation needs. These products embody circular economy principles by promoting resource efficiency and environmental sustainability, demonstrating a closed-loop system that minimises waste and reduces greenhouse gas emissions. Integrating composting and product development from tea waste exemplifies a sustainable approach that aligns with reducing landfill burden and fostering carbon neutrality. Future research should focus on optimising composting techniques and evaluating the long-term impact on soil health, further supporting adopting these sustainable agricultural practices.

Table 1: Fresh weight, dry weight and volume of compost at different points of decomposition

Point of decompostion	Fresh Weight (gm)	Dry weight (gm)	Volume (ml)
0-30 days	500	433	110
30-60 days	476	351	84
60-90 days	360	242	63
90-100 days	315	232	49

Table 2 : Constituents of natural glue prepared for making mulching sheet from tea waste

Sl. No	Ingredients	Quantity
1.	Devils Tree (*Alstonia scholaris*) sap; Fam., Apocynaceae	15 ml
2.	Bahot tree (*Artocarpus lacucha*) sap; Fam., Moraceae	10 ml
3.	Black lentil (*Vigna mungo*) Fam., Fabaceae	40 g
4.	Sticky rice (Bora)	100 g
5.	Duck eggs	2 Nos
6.	Dhuna (resin)	40 g
7.	Shredded Tea Waste	200 g
8.	Chopped dry tea leaves	800 g
9.	Water	2000 ml

Table 3 : Methods for Processing Tea Waste into Peat and Mulching sheet

Step	Method/Instrument	Purpose/Description
Collection	Collection tools	To gather tea waste from the tea production process
Drying	Drying ovens or sun drying	To reduce the moisture content of the tea waste, making it suitable for further processing
Grinding	Shredding machine	To break down dried tea waste into fine particles or powder
Mixing	Manual mixing	To combine tea waste powder with binding agents and additives
Peat Formation	Compression mold	To compress the mixed tea waste into peat block-like structures for use as soil amendments
Sheet Formation	Sheet forming press	To press the mixed tea waste into thin sheets for various applications
Drying (Peat/Sheets)	Oven or sun drying	To remove excess moisture from the formed peat and sheets, ensuring stability and usability

Table 4 : pH and Moisture of products from tea waste

Condition	pH	Moisture (%)
Compost (Control condition)	6.61	44.56
Compost (Polyhouse)	7.04	42.31
Tea peat	6.27	24.62
Mulching sheet	6.85	15.82

Table 5 : Major Nutrient of different products from tea waste

Major Nutrients	Nitrogen(N) (%)	Phosphorus (P) (%)	Potassium (K) (%)	Sulphur (S) (%)	Calcium (Ca) (%)	Magnesium (Mg) (%)
Compost (Control condition)	1.57	0.77	0.95	0.17	0.53	0.05
Compost (Polyhouse)	1.83	0.78	1.24	0.27	0.55	0.05
Tea peat	0.34	0.49	1.98	0.53	0.28	0.08
Mulching sheet	0.45	5.03	1.07	0.56	0.58	0.07

Table 6 : Micronutrient of products from tea waste

Condition	Zn (ppm)	Cu (ppm)	Mn (ppm)	Fe (ppm)
Compost (Control condition)	15.9	116.6	66.47	170.67
Compost (Polyhouse)	18.2	108.8	71.66	189.22
Tea peat	58.67	87.98	100.83	104.83
Mulching sheet	19.42	79.77	63.42	70.25

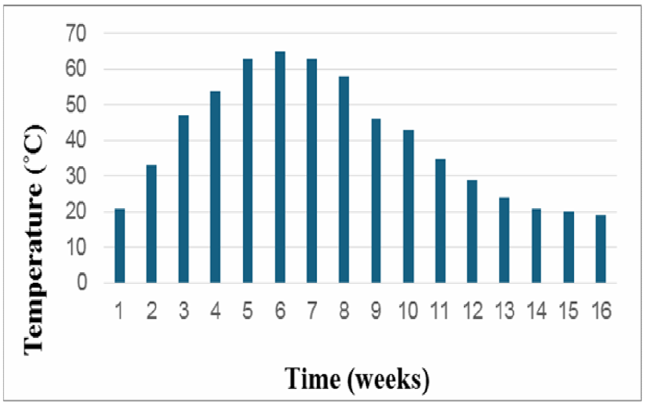

Fig. 1 : Temperature progression during composting of tea waste

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