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Research Article

Enhancing Fiber Yield and Environmental Sustainability through Integrated Fertilization Strategies and waste valorization of Ramie (*Boehmeria nivea L*)

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Highlights

1. Integrated faming using biofertilizer and inorganic fertilizer in sub optimal doses for fiber yield enhancement of Ramie.

2. Sustainability of soil fertility upto 3rd harvest (more than 180 days) with integrated farming.

3. Environmental sustenance through Ramie decorticated waste valorization as briquette.

Abstract

Ramie (*Boehmeria nivea*) is one of the oldest natural fiber plants with the best fiber quality in terms of strength and lustre of processed fiber. Ramie can be an essential component in the natural fiber-based textile market due to its excellent properties. Synthetic fibers are non-biodegradable finite resources, and hence, there is a need to replace synthetic fibers with natural fibers. The processing of Ramie fiber for fine yarn production is improving with every passing day. However, the challenge lies in ensuring a consistent supply of raw Ramie fiber for commercial purposes while minimizing environmental damage. The climate of the north-eastern states of India is favourable for Ramie cultivation, but the lack of community awareness and scientific cultivation manuals are the major constraint towards commercial-scale Ramie cultivation. Ramie is a rapidly growing plant that requires adequate fertilizer application for growth from the 2nd year onwards up to the 16th year after plantation. The leaching of inorganic fertilizer (IF) used in the cultivation of Ramie has adverse environmental impacts. In this study, sustainable Ramie cultivation with a combination of IF and bacterial biofertilizer (BF) at a 1:1 combination gave a significant increase in biomass and fiber yield when compared to IF or BF alone, hence it is suitable for adoption in real-time application. The mode of action is ensuring the availability of nitrogen (N), phosphorus (P), and potassium (K) through application of IF while preventing their leaching into the environment by restricting them in the plant root zone, indirectly facilitating their uptake. The briquette formed using decorticated waste [produced at the rate of 3.92 kilograms (kg) per kg of fresh decorticated fiber] released sustained energy on burning, produced higher yield of essential oil from lemongrass leaf compared to firewood or a 100% bamboo briquette. Hence, this paper reports environmental protection through process optimization from cultivation to end-product valorization through eco-friendly product development.

Keywords
bacterial biofertilizer; inorganic fertilizer, ramie fiber, sustainable cultivation, waste valorization

Introduction

The textile industry in India is rapidly growing, accounting for 14% of total industrial manufacturing [1,2]. The primary raw materials used in textile industries are synthetic fibers, natural fibers, synthetic dyes, chemicals, and water [1]. Cultivation of natural fibers increased the competition for food production due to limited agricultural land [3]. On the other hand, synthetic fibers dominate the manufacturing industries. However, synthetic fibers are non-biodegradable and not ecofriendly [4]. Natural fiber-based textiles, such as hemp, silk, jute, cotton, and Ramie, can be an appropriate substitute for synthetic fibers [5]. Ramie (*Boehmeria nivea*), also known as Chinese silk or China grass, is one of the strongest, longest, and oldest natural bast fiber plants [6,7,8]. Ramie fibers have excellent properties, including high tenacity, tensile strength (much greater than cotton and silk), lustre, thermostability (>200°C), and moisture-absorption properties, and produce excellent fabric after degumming [6,9,10,11]. Ramie has the highest length-to-breadth ratio of 3500, making it suitable for fine yarn preparation. There are around 100 species of Ramie, with 19 species reported in India [6,7]. The two most common Ramie species are white Ramie and green Ramie. Ramie, a plant native to southwestern China, has been used for clothmaking and mummification since ancient times. Originating in the mountain valleys of southwest China, it was a major fiber used before cotton arrived around AD 1300. This plant grown in tropical, subtropical, and temperate regions globally [6,7]. China, Indonesia, the Philippines, Korea, Vietnam, and Japan are the major raw material suppliers globally, with China accounting for more than 95% of world production [8,10]. Around 72,934 hectares (ha) of area is under Ramie cultivation in China [8]. Literature shows about 320 ha of land cultivates Ramie throughout India. In India, Ramie is grown in Assam, Arunachal Pradesh, Manipur, Meghalaya, Nagaland, Mizoram, and the northern part of West Bengal [7]. However, Ramie is also grown in Kharagpur, Tripura, and Bhubaneswar for research purposes [12]. In India, Ramie is known as Rhea, Popah, KhunKoora, Kurkunda, etc. [13]. Despite the huge demand for Ramie fiber, production is very low [14]. India has suitable climatic conditions for Ramie cultivation; but raw Ramie fibers are imported from other producing countries [8]. Ramie is a versatile fiber used in various industries, including traditional custom hanbok in Korea and kimono material in Japan. Ramie fibers can be blended with other fibers to create high-quality dress materials, tablecloths, towels, napkins, and canvas [6,11,15]. Ramie can also be used for bioethanol production, as medicines, as animal feed, and as mulch [16]. Its protein-rich leaves can be used as animal feed [17].

Ramie can be grown in various climatic conditions and soil types, with better growth and fiber yields occurring in areas with favourable climatic conditions and soil types [18]. Deep, fertile sandy-loamy soils are preferred to retain the moisture. Such organic matter-rich soil with a pH of 6-7 is preferred [7,18] for Ramie cultivation. From sandy soil, both water and fertilizer leach out, and in clay soil, the root system development gets obstructed due to compaction on drying. An average of 1500–2500 mm of rainfall is suitable for Ramie cultivation, with temperatures between 25°C and 31°C [7,18]. Ramie stems start to turn brown, requiring harvesting before attaining maximum height if the rainfall is less than 1000 mm [18]. Ramie cultivation requires adequate moisture, but waterlogging should be avoided [8,18]. Vegetative propagation of Ramie can be done through rhizome cuttings, plantlets, stem cuttings, and seeds [7,18]. Ramie can be grown throughout the year under irrigated conditions using flat planting or ridge and furrow planting methods [7,18]. The ideal distance between rows is 60 centimetres (cm), and between plants is 30 cm [7,19]. According to Oshiumi (1951), the plantation time of Ramie is late March to early April in the warmer area and late April in cooler areas [18]. Ramie can be harvested up to six times a year under ideal conditions [6]. Farmers can start harvesting from the second year every 45 days for up to 16 years [11]. Harvesting can be done by cutting the stem a few cm above the root [6]. Ramie fibers are extracted through the decortication method, which removes outer bark, cortex, and pectin, followed by washing and drying [6]. Decorticated waste generated during fiber production, can be used as mulch, reducing waste and making the process more profitable and environmentally friendly [8]. The yield of Ramie fiber ranges from 1600 to 2200 kg ha^{-1} [7,20]. The fiber recovered represents only 4-5% of the total plant biomass [6]. The cost of raw Ramie fiber was INR 115 kg^{-1} [8] and varies based on demand between INR 90 and INR 200 kg^{-1}. Fertilizers, primarily N, P, and K, are important for plant growth [21]. Routine fertilization is needed to maintain soil health and to enhance fiber yield [7,8,18]. It was reported that N and P enhanced the Ramie fiber yield, whereas K improved the quality of the fiber [22]. However, chemical fertilizers have adverse environmental impacts due to leaching, and overuse of chemical fertilizers can reduce the essential micronutrients in soil [23]. Organically rich soil and proper fertilization positively impact fiber yield [24]. Ray Chaudhuri et al. (2021) reported that biofertilizer-based cultivation improves fiber yield with maintained soil nutrients [8]. Gogoi et al. (2021) reported that ammonia-rich liquid biofertilizer enhanced Ramie fiber yield [25]. Integrated Nutrient Management (INM), like organic, inorganic, and microbial inoculants for enhancing the crop yield, is crucial for proper consumption of resources in a sustainable approach [26]. A patented [27] BF with indole acetic acid (IAA, a derivative of auxin) secreting ability restricts the nitrate and phosphate in the root zone up to 11 cm and thereby prevents leaching of unutilized fertilizer, which furthermore helps in plant growth [28]. This BF (a 1:1 combination of aerobic and anaerobic consortium) has been reported to promote growth of mung bean, lemongrass, and cassava [28, 29]. The BF is made up of two bacterial consortiums namely NB1 which is an anaerobic consortium (*Pseudomonas* sp, *E. coli*, and uncultured bacterium in a ratio of

44:37:19) and an aerobic BN7 (*Pseudomonas* sp., *Bacillus* sp., *Azoarcus* sp., and uncultured bacterium in a ratio of 20:3:31:46). While NB1 was isolated from soil of East Kolkata Wetland, BN7 was isolated from the immobilized biomass of nitrate reducing bioreactor at the Waste Management Department of Bhabha Atomic Research Center, Mumbai, India in nitrate broth [28, 30]. The consortia were selectively enriched in nitrate broth from the environmental samples. After multiple rounds of cultivation and characterization, the consortia when mixed in 1:1 proportion [27] could prevent leaching of nitrate from the soil upto 11cm depth [28]. Pot trial experiments confirmed enhanced yield with higher chlorophyll content of the leaves, hence, leading to the development of this biofertilizer formulation [27, 31]. In order to use a BF at a commercial scale, it is essential to test its performance on a variety of crops before recommending it for large-scale application. Hence, in this current study, the authors hypothesize that a combination of BF and IF at lower than recommended dose can enhance plant growth and fiber yield through sustained supply of plant growth nutrients throughout the growth period, preventing nutrient leaching and so retaining soil fertility. Ramie cultivation was carried out under four conditions: a control (no fertilizer) condition, using IF, BF, and a combination of IF and BF at half the recommended dose.

Materials and Methods

1. Agronomy

1.1. Location of the experiment

The experiment was conducted at Tripura University premises (23.9408° latitude and 91.9882° longitude), Tripura, India. The cultivation duration was April 2023 to February 2024. The average temperature of the area varied from 18°C to 28°C.

1.2. Cultivation of Ramie

To check the impact of different fertilizers on agronomic parameters and yield of Ramie, a standard variety of Ramie (var. R1411) was cultivated. Ramie cultivation was carried out from April 2023 to February 2024 with four different treatments:
T0 = Control (no fertilizer),
T1 = 100% IF,
T2 = 100% BF,
T3=Combination of 50% IF and 50% BF.

Ramie plantation was conducted by adopting ridge and furrow planting methods to avoid waterlogging during the rainy season. The distance between two rows was 60 cm and between two consecutive plants in a row was 30 cm. The furrows were in the north to south direction to ensure adequate sunlight. The area of each field was 13.86 m^2. Rhizomes measuring about 12–15 cm were taken from 3- to 4-year-old plantations and planted within 72 hours of collection to retain viability. Rhizomes were placed horizontally into the soil about 5 cm deep and covered with soil. Applications of IF (with irrigation), BF, and a combination of IF and BF were done in their respective fields immediately after plantation of the rhizome. In the control field, no fertilizer application was done. Fertilization was done only once during the planting of rhizomes. As per Gogoi (2022), the recommended dose of 100% IF used in this study includes N, P, and K in a ratio of 20:15:15 kg/h (60.15 g urea, 129.93 g single superphosphate, and 33.264 g murated potash) [19], and the 100% dose of BF was 1.33 L/m^2 with 3.68×10^{9} cells/m^2 [30]. The combination (IF+BF) was made up of 50% IF (N:P:K 10:7.5:7.5 kg/h) and 50% BF (0.665 L/m^2 with $1.84\text{x}10^{9}$ cells/m^2). Nitrate broth was prepared and autoclaved at 121ºC for 15 minutes (15 psi) in order to prepare BF. Following an overnight contamination check at 37°C, 1% anaerobic consortium was inoculated into degassed (purged with CO_2 and N_2) vials and 1% aerobic consortium was inoculated into conical flasks containing sterile nitrate broth, respectively. After 24 hours of confluent growth, the two bacterial consortiums were mixed in a 1:1 ratio and applied to the field.

1.3. Data collection

Matured stems were harvested by cutting just above the ground. The first harvest took 106 days for the maturation of the stem. The second harvesting was done 50 days after the first harvesting, and the third harvesting was done 30 days after the second harvesting. The harvesting is done as the stem starts showing a change in colour (brown) from above the ground level. Harvesting was done using a sickle. The height of the stem was measured using a measuring tape, the diameter of the stems was measured using a vernier calliper, the number of stems per plant was counted, and stem weight per rhizome (leaf weight plus strip weight), strip weight (stem without leaves) per rhizome, and fiber weight per rhizome were measured using a weighing balance (SF-400) and documented after every harvest. The stems were decorticated by using a decorticator machine (Akriti, India). After decortication, Ramie fibers were dipped into water with a 1:8 fiber-to-liquid ratio. After 6 hours of dipping, the Ramie fibers were washed with tap water and dried in the sun [11].

1.4. Soil analysis

The soil was collected pre-cultivation and post-cultivation for T3 treatment after third round of harvesting (186 days) The chemical parameters were analysed in terms of concentration of N [32](IS 14684-1999), P [33](IS 6361:1971), K [34](IS 9497:1980), sodium [34](IS 9497:1980), magnesium [35](IS 5949:1990 RA 2003), and organic matter [36][IS 2720 (Part XXII): 1972] through an outsourcing facility (Precision Laboratory, Kolkata, India).

1.5. Data analysis

The recorded data of every harvest was analysed through an F-test followed by a T-test to check the significant difference between the treatments at a 95% confidence level. The treatments compared were T0 and T3, T1 and T3, and T2 and T3. The graphical representation was done using the software GraphPad Prism 8.0.1.

2. Ramie briquette as a fuel source

Ramie decorticated waste collected after fiber extraction through decortication was oven-dried. A portion of the waste was ground using a mixer grinder. The particle size of the ground waste used for forming the pellet was measured. Thirty particles were measured, and the result was expressed as mean ± standard error. The ground waste was used for pellet formation without additives in a pelletizer (KBr Press) at UGC DAE Centre Kolkata (India) using 100 kg cm^{-2} pressure for 30 seconds. This was done to test the self-adhering property of the material. The particle as well as the pellet formed were visualized under a Field Emission Scanning Electron Microscope (SUPRA 55 VP-4132 Carl Zeiss) with platinum coating as per standard protocol [29]to visualize the surface structure and understand the reason behind the self-adhering property. The oven dried Ramie decorticated waste was converted to briquettes at the industry (G-Cube Sticks Pvt Ltd) using 80% Ramie waste and 20% bamboo waste (dust formed after stick making) maintained at a moisture level of 7 to 10% using a compression force of 2 tons per kilogram pressure. The formed briquettes were used as an alternative fuel source, replacing firewood during lemongrass oil extraction using an indigenous steam distillation system.

Results

1. Average number of stems

The average number of stems per rhizome was found to be 16.50±5.47, 26.65±8.65, and 29.23±9.66 during the 1st, 2nd, and 3rd rounds of harvesting with T3 treatment, which was significantly higher as compared to T0, T1, and T2 during the 1st harvest (6.74±3.30, 9.13±4.41, and 7.52±4.24 with p-values of 4.54E-05, 3.14E-05, and 8.93E-07, respectively), 2nd harvest (12.23±5.51, 13.35±5.43, and 13.55±6.53 with p-values of 8.97E-05, 1E-04, and 2.70E-06, respectively), and 3rd harvest (13.19±5.50, 15.52±5.33, and 14.26±5.71 with p-values of 1E-04, 3.8E-04, and 1.5E-04, respectively). The plants treated with T0 had the least number of stems, and T3 experienced the highest number of stems during all the harvests, as shown in Figure 1.

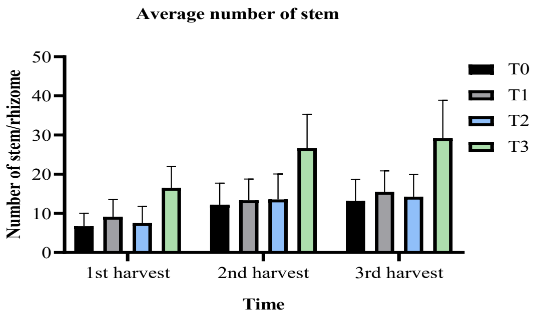

Figure 1: Average number of stems per rhizomes using different fertilization regime.

2. Average height of stem

Figure 2 shows that the average height of stems was highest with T3 treatment, and the height of stems was 91.24±21.51 cm, 93.10±21.64 cm, and 95.79±12.41 cm during the 1st, 2nd, and 3rd harvests, respectively. The average height of T3-treated plants was found to be significantly superior to that of T0, T1, and T2 during the 1st harvest (52.74±15.81 cm, 51.06±17.72 cm, and 46.38±12.18 cm with p-values of 8.9E-08, 1.7E-07, and 1.4E-05, respectively), 2nd harvest (61.40±16.63 cm, 58.55±14.03 cm, and 62.96±15.65 cm with p-values of 5.63E-06, 1.3E-04, and 6.85E-06, respectively), and 3rd harvest (63.48±12.91 cm, 67.56±19.13 cm, and 67.86±11.17 cm with p-values of 4.96E-09, 2.47E-05, and 1.18E-08, respectively).

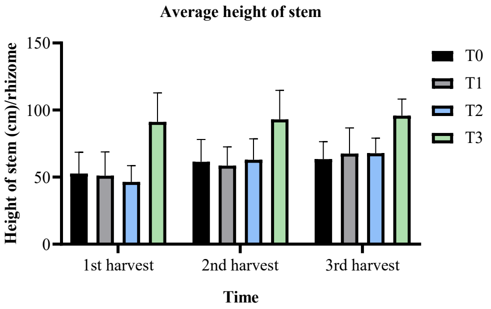

Figure 2: Average height of stems (cm) per rhizomes using different fertilization regime.

3. Average diameter of stem

The average diameter of the stem shown in Figure 3 was significantly improved using T3 treatment (12.09±3.04 mm) as compared to T0 (4.45±1.36 mm), T1 (6.45±1.52 mm), and T2 (4.71±1.64 mm) during the 1st round of harvesting, with p-values of 3.1E-06, 3.7E-05, and 2.9E-06, respectively. During the 2nd round of harvesting, the diameter of the stem was significantly higher with T3 treatment (13.30±4.54 mm) as compared to T0 (7.13±1.48

mm), T1 (8.06±1.84 mm), and T2 (6.61±1.89 mm) with a p-value of 5.1E-04, 1.6E-03, and 3E-04, respectively. Similarly, the average diameter of stems was significantly higher with T3 treatment (14.81±3.35 mm) during the 3rd round of harvesting as compared to T0 (7.26±1.32 mm), T1 (9.13±2.23 mm), and T2 (7.61±1.26 mm) with p-values of 8.01E-06, 8.25E-05, and 1.22E-05, respectively.

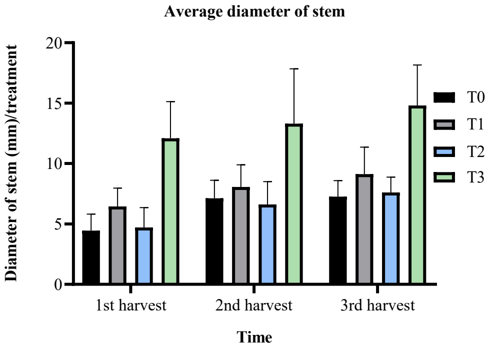

Figure 3: Average diameter of stem (mm) using different fertilization regime.

4. Average weight of stem

The average weight of stem per rhizome (Figure 4) with T3 treatment was found to be 574.05±250.73 g, 1216.44±693.94 g, and 1320.53±584.34 g during the 1st, 2nd, and 3rd rounds of harvesting, respectively, which was significantly enhanced as compared to T0, T1, and T2 during the 1st harvest (244.55±118.97 g, 234.35±103.47 g, and 188.39±103.30 g with p-values of 6.2E-04, 5.6E-04, and 2.2E-04, respectively), the 2nd harvest (364.61±155.35 g, 539.61±414.40 g, and 368.87±235.91 g with p-values of 1.1E-03, 4.6E-03, and 1E-03, respectively), and the 3rd harvest (443.77±260.21 g, 689.94±330.24 g, and 424.45±218.25 g with p-value of 2.7E-04, 2.6E-03, and 2.1E-04, respectively).

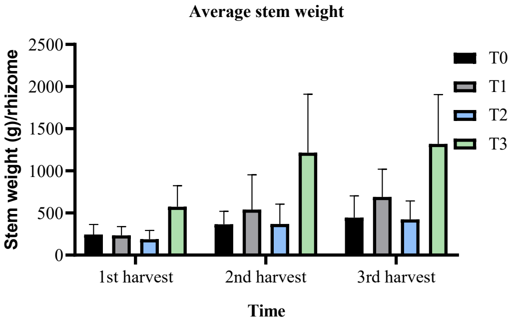

Figure 4: Average stem weight (g) per rhizome using different fertilization regime.

5. Average strip weight

The average strip weight (Figure 5) was 280.88±123.87 g with T3 treatment, which was found to be significantly increased as compared to T0 (107.77±58.01 g), T1 (123.35±67.89 g), and T2 (101.84±57.21 g) during the 1st harvesting with p-values of 3.9E-04, 8.6E-04, and 2.9E-04, respectively. Similarly, during the 2nd round of harvesting, the strip weight was significantly higher with T3 treatment (555.34±309.94 g) than T0 (189.61±83.73 g), T1 (223.32±169.39 g), and T2 (197.71±126.24 g) with p-values of 1.3E-03, 2.7E-03, and 1.7E-03, respectively. Average strip weight was significantly higher with T3 treatment (774.25±337.91 g) during the 3rd harvesting as compared to T0 (239.87±144.19 g), T1 (344.10±193.62 g), and T2 (235.48±120.82 g) with p-values of 1.76E-04, 8.87E-04, and 1.53E-04, respectively.

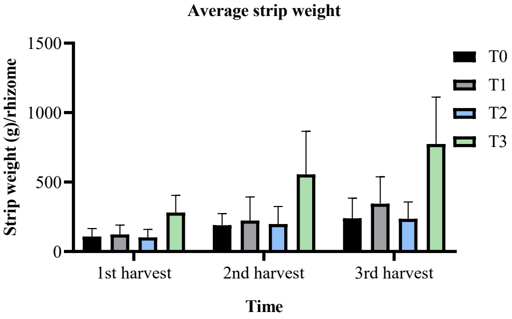

Figure 5: Average strip weight (g) per rhizome using different fertilization regime.

6. Fiber yield

Like other agronomic parameters, the average fiber weight (Figure 6) was also significantly enhanced using T3 treatment (4.58±1.92 g) as compared to T0 (1.29±0.70 g), T1 (2.34±1.29 g), and T2 (1.73±0.97 g) during the 1st round of harvesting, with p-values of 1.3E-04, 2.2E-03, and 3.7E-04, respectively. The T3 treatment (25.97±14.50 g) also showed significantly higher fiber weight during the 2nd round of harvesting as compared to the T0 (8.34±3.68 g), T1 (8.93±6.78 g), and T2 (7.12±4.54 g) with p-values of 1.3E-03, 1.4E-03, and 6.9E-04, respectively. Similarly, the average fiber weight was significantly higher with T3 treatment (22.81±9.95 g) during the 3rd harvest as compared to T0 (9.35±5.62 g), T1 (10.32±5.81 g), and T2 (9.89±5.07 g) with a p-value of 5.65E-04, 8.64E-04, and 7.12E-04, respectively.

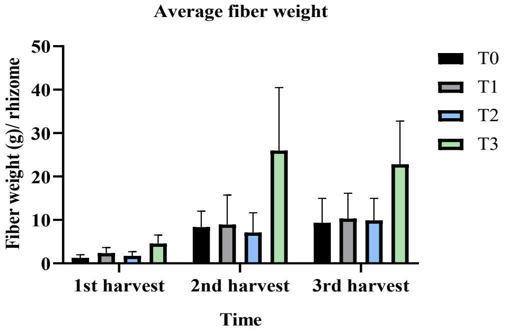

Figure 6: Average fiber weight (g) per rhizome using different fertilization regime.

All the above parameters were assessed post 3rd harvest (4th harvest after 45 days of 3rd harvest, 5th harvest after 45 days of 4th harvest, and 6th harvest after 45 days of 5th harvest), as shown in Table 1. In the case of fiber weight, there was an increase from treatments T0, T1, and T2, while there was a decrease in T3, resulting in an overall insignificant difference among the treatments from the 4th harvest onwards. Hence fertilizer reapplication will be recommended after the 3rd harvest for maintaining fiber yield. In the case of stem weight, there was insignificant variation between T3 and T1 during the 4th harvest, showing that the IF application shows a gradual increase in yield. In the case of the height of the stem, there was a significant increase even after the 4th and 6th harvests for treatment T3 as compared to T1. For the number of stems and diameter of the stem, there was a significant increase in the case of treatment T3 at the 4th, 5th, and 6th harvests. In the case of strip weight, the 4th and 5th harvests show insignificant differences between T3 and T1 (with T3 being higher), while the 6th harvest shows significant differences between the same combinations. (Table 1). The statistical data is shown in supplementary Table S1.

Table 1: Tabulation of the agronomic parameters of Ramie cultivation with four treatments (T0, T1, T2, T3) over 6 harvests.

Agronomic parameters	Time	T0	T1	T2	T3
Numbers of stem	1st harvest	6.74±3.30	9.13±4.41	7.52±4.24	16.50±5.47
	2nd harvest	12.23±5.51	13.35±5.43	13.55±6.53	26.65±8.65
	3rd harvest	13.19±5.50	15.52±5.33	14.26±5.71	29.23±9.66
	4th harvest	12.87±5.87	14.71±4.89	13.87±5.48	23.43±5.70
	5th harvest	13.61±5.49	15.29±5.43	12.06±5.10	21.64±6.09
	6th harvest	14.38±6.87	15.80±5.69	13.74±5.86	23.04±7.12
Height of stem (cm)	1st harvest	52.74±15.81	51.06±17.72	46.38±12.18	91.24±21.51
	2nd harvest	61.40±16.63	58.55±14.03	62.96±15.65	93.10±21.64
	3rd harvest	63.48±12.91	67.56±19.13	67.86±11.17	95.79±12.41
	4th harvest	83.83±20.41	94.57±17.93	79.49±18.47	128.28±49.77
	5th harvest	65.44±24.17	79.33±25.06	55.55±13.60	101.61±61.24
	6th harvest	69.65±18.54	78.93±26.73	58.60±18.64	110.50±19.56
Diameter of stem (mm)	1st harvest	4.45±1.36	6.45±1.52	4.71±1.64	12.09±3.04
	2nd harvest	7.13±1.48	8.06±1.84	6.61±1.89	13.30±4.54
	3rd harvest	7.26±1.32	9.13±2.23	7.61±1.26	14.81±3.35
	4th harvest	8.65±1.11	8.23±0.88	8.16±1.59	10.49±2.88
	5th harvest	8.94±2.46	9.58±1.93	8.55±1.85	11.70±3.27
	6th harvest	9.06±2.28	9.16±2.37	8.93±1.89	15.17±2.84
Stem weight (g)	1st harvest	244.55±118.97	234.35±103.47	188.39±103.30	574.05±250.73
	2nd harvest	364.61±155.35	539.61±414.40	368.87±235.91	1216.44±693.94
	3rd harvest	443.77±260.21	689.94±330.24	424.45±218.25	1320.53±584.34
	4th harvest	671.52±466.62	851.42±552	507.10±295.91	960.50±255.82
	5th harvest	576.32±464.36	838.32±667.64	370.48±303.12	1218.83±1073.55
	6th harvest	537.12±435.58	883.83±756.58	329.64±206.34	1739.67±909.13
Strip weight (g)	1st harvest	107.77±58.01	123.35±67.89	101.84±57.21	280.88±123.87
	2nd harvest	189.61±83.73	223.32±169.39	197.71±126.24	555.34±309.94
	3rd harvest	239.87±144.19	344.10±193.62	235.48±120.82	774.25±337.91
	4th harvest	382.42±275.59	468.39±322.43	287.58±167.34	522.06±176.91
	5th harvest	315.87±269.48	508.23±409.56	189.45±161.32	954.15±943.59
	6th harvest	336.74±293.97	543.09±454.82	191.16±116.97	1113.93±753.80
Fiber weight (g)	1st harvest	1.29±0.70	2.34±1.29	1.73±0.97	4.58±1.92
	2nd harvest	8.34±3.68	8.93±6.78	7.12±4.54	25.97±14.50
	3rd harvest	9.35±5.62	10.32±5.81	9.89±5.07	22.81±9.95
	4th harvest	17.10±12.32	17.35±11.95	15.77±9.18	20.35±9.37
	5th harvest	16.55±14.12	17.26±13.91	16.73±14.24	27.55±29.46
	6th harvest	16.63±14.52	18.89±15.82	16.47±10.08	25.70±17.39

From the above data, it is clear that Ramie cultivation using T3 can reduce the IF use by 50% without compromising the productivity. Moreover, 1.80-fold, 1.99-fold, and 1.88-fold higher numbers of stems were obtained by T3 treatment than T1 treatment alone during the first, second, and third rounds of harvesting, respectively. The height of stems was 1.78-fold, 1.59-fold, and 1.41-fold higher with T3 treatment than T1 treatment alone during the first, second, and third rounds of harvesting, respectively. The diameter of stems was 1.87-fold, 1.65-fold, and 1.62-fold higher with T3 treatment than T1 treatment alone during the first, second, and third rounds of harvesting, respectively. In the case of stem weight, 2.44-fold, 2.25-fold, and 1.91-fold enhancements were seen with T3 treatment compared to T1 treatment alone during the first, second, and third rounds of harvesting, respectively. The strip weight was 2.27-fold, 2.48-fold, and 2.25-fold higher with T3 treatment than T1 treatment alone during the first, second, and third rounds of harvesting, respectively. It was found that 1.95-fold, 2.9-fold, and 2.20-fold higher fiber yields were obtained by T3 treatment than T1 treatment alone during the first, second, and third rounds of harvesting, respectively. According to Ray Chaudhuri et al. (2017), the BF works by restricting the nutrients in the root zone up to 11 cm. Hence, 50% BF used in the T3 treatment may restrict the 50% IF (N, P, K) in the root zone, ensuring steady availability of nutrients during the entire growth season and ensuring enhanced plant growth

[27]. It was found that BF alone cannot sustain the nutritional demand of Ramie. Hence, when combined with IF, it can ensure a continuous supply of nutrients to the plant root zone and its uptake by the plants. This would in turn decrease the soil nutrients, requiring replenishment after a certain duration to sustain production.

7. Soil analysis

Ramie is rapidly growing plant which requires adequate fertilization. Nutrient composition of the soil before and after Ramie cultivation with combination treatment revealed that 50% microbial inoculation facilitates the uptake of nutrients such as N, P, K, sodium, magnesium, and organic matter by the plant (Table 2). This in turn ensured significantly higher plant growth and fiber yield with T3 treatment. In order to maintain soil fertility, there is a need to replenish the plant growth nutrients into the soil after a few (3^{rd}) rounds of harvesting.

Table 2: Nutrient composition of the soil before and after Ramie cultivation with combination treatment.

Treatments	**Available Nitrogen as N (mg/100g)**	**Available Phosphorus as P (mg/100g)**	**Available Potassium as K(mg/kg)**	**Sodium as Na (mg/kg)**	**Magnesium as MgO (mg/100g)**	**Organic Matter (% w/w)**
Pre-cultivation	8.4	2101.6	81.53	9.94	4009.9	0.671
Post cultivation	8.0	80	23.77	4.38	98.61	0.655

8. Briquettes of Ramie decorticated waste

The ground oven-dried Ramie decorticated waste particles were 1.45±0.69 mm in length. Under the scanning electron microscope, an uneven surface with gum-like material was observed (Figure 7a). Upon pelletization without binder, it formed strong and stable pellets of various thicknesses (Figure 7b), which under FESEM showed a rough gummy appearance (Figure 7c). The presence of gum in the waste might be responsible for its self-adhering property. Ramie briquettes made using 80% Ramie decorticated waste and 20% bamboo waste, as shown in Figure 7d, when used as fuel for lemongrass essential oil during hydrodistillation, yielded more oil within one hour as compared to firewood and 100% bamboo briquettes. The total weight of the fuel used was also less in the case of Ramie: Bamboo briquettes than Bamboo briquettes or firewood (Table 3). In order to sustain combustion for one hour, only 48.03% of the weight of Ramie briquettes (compared to firewood) was required. The oil extraction was highest with the Ramie: Bamboo briquette, followed by the bamboo briquette and then firewood, indicating a sustained heat release over the entire period resulting in higher oil production. Hence, blending the dried, decorticated Ramie waste with bamboo can enhance its calorific value, ensuring valorization of the waste into eco-friendly, economical by-product generation.

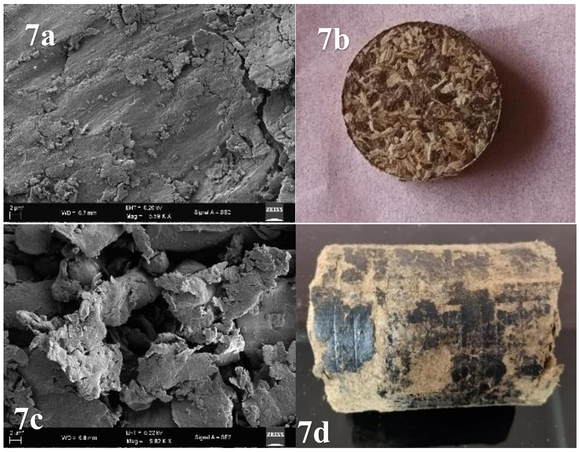

Figure 7a: FESEM image of grounded Ramie biomass particle (5.59KX magnification), 7b: Ramie pellet, 7c: FESEM of the Ramie pellet at 5.82KX magnification, 7d: Ramie briquette (80% Ramie decorticated waste and 20% bamboo waste)

Table 3: Weight of briquette and firewood used in on hour and amount of oil extracted from one kilogram of leaf in oil hour through indigenous stream distillation.

Briquette types	**Briquettes used per hour (kg)**	**Oil extracted within one hour (g) per kg of leaves**
Firewood (100%)	4.309 kg	1.784 g
Bamboo (100%)	2.252 kg	1.851 g
80% Ramie decorticated waste+20% Bamboo waste	2.070 kg	2.647 g

Discussion

Literature shows that nitrogen fertilizer application enhances plant growth and Ramie fiber yield [22]. Wang et al. (2024) conducted a pot trial study with four bacterial strains of *Bacillus velezensis*, where plant growth promotion was observed [37]. Crop yield may be decreased when the quantity of chemical fertilizer is reduced [38]. However, there are studies reporting maintained yield when the chemical fertilizer is coupled with biofertilizer in 1:1 to 1:2 ratio with 50% reduction in quantity of chemical fertilizer application [39, 40]. This would ensure better uptake of the nutrient with prevention of leaching as seen in the current study. Biofertilizer often results in higher yield (as in case of coffee) due to prevension of root damage by nematode infestation [41].

According to Ray Chaudhuri et al. (2021), Ramie cultivation using vermicompost significantly increased the average height of the stem, basal diameter, and fiber yield as compared to chemical fertilizer [8]. In the present study, T3 significantly increased the agronomic parameters, including the number of stems, diameter of stems, height of stems, stem weight, strip weight, and fiber weight, as compared to T0, T1, and T2. The BF used in this current study restricts the nutrients to the root zone and ensures available nutrients for the plant, thereby preventing the leaching of nutrients. This BF also works efficiently on mung beans and okra [31] and lemongrass and cassava [29], as per earlier reports. In these cases, 100% BF significantly increased the yield and quality of the organic produce, completely replacing the use of IF without compromising the productivity. However, unlike other tested crops mentioned above, cultivation of Ramie using this BF alone compromised the yield. It required a combination of 50% of the recommended dose of IF with 50% of the recommended dose of BF to ensure enhanced productivity. This might be because of the higher fertilization requirement for supporting this exuberant growth of Ramie. This combination ensured that the reserve of NPK provided by IF is prevented from leaching due to washing out by the BF in the root zone, ensuring its constant uptake by the plant. However, as seen from Table 1 and the supplementary data, the fertilizer needs to be reapplied, preferably after the 3rd harvest, in order to ensure sustained production. It was clear from this study that the performance of BF varies from crop to crop. Therefore, testing the BF on different varieties of crops is necessary before moving towards commercial-scale production. This study also finds that Ramie decorticated waste, which is often dumped into the landfill, can serve as an alternative fuel source with maximum combustion and therefore could reduce greenhouse gas emissions.

Conclusions

Ramie can be a major fiber crop in the natural textile market. The climate of Tripura and other northeastern states of India is suitable for Ramie cultivation. Proper nutrient management with scientific intervention can improve the productivity per unit of land area, which will reduce the dependency upon synthetic fibers. A combination of IF and BF minimizes the use of IF to 50% of the recommended dose with enhanced productivity, with minimized plant growth nutrient leaching, which furthermore reduces the environmental damage. Hence, these findings suggest that integrated nutrient management is beneficial for sustainable cultivation of Ramie with use of health rhizome from 3 to 4 years old plantation, within 72 hours of uprooting with adequate moisture during the cultivation but avoiding water lodging. Furthermore, the developed formulation needs to be tested for scalability of the process and the impact of soil type and climate on Ramie growth. This shall be followed by a life cycle analysis to understand the environmental impact of the developed scheme of cultivation to the valorization of the waste.

List of abbreviations

AD- Anno Domini, INR- Indian Rupee, INM-Integrated Nutrient Management, IAA- Indole acetic acid, N- Nitrogen, P- Phosphorus, K-potassium, BF- Biofertilizer, IF- Inorganic fertilizer, T0- Control (no fertilizer), T1-100% Inorganic fertilizer, T2-100% Bacterial biofertilizer, T3- Combination of 50% inorganic fertilizer and 50% bacterial biofertilizer, m^2- Square meter, L- Liter, h- hectare, g-grams, kg- kilogram, mm-millimeter, cm-centimeter, IS- Indian standard.

Author Contributions

Conceptualization, validation, funding acquisition, writing—review and editing, resources, supervision, project administration: Shaon Ray Chaudhuri; Writing—original draft preparation, investigation, data curation, methodology, formal analysis, software, visualization: Espita Palwan; Investigation, data curation, methodology, formal analysis: Abinash Debbarma; Data curation: Sampili Debbarma.

Availability of Data and Materials

The data supporting the findings of this study are included within the manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

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Figures 1 to 6 were generated by using GraphPad Prism 8.0.1.

Supplementary Material

Supplementary material associated with this article has been published online and is available at: Link to the DOI

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