Review of different composting methods towards end product quality, cost of production, process adoptability potential, post soil application efficacy and ghg mitigation potential fundamental factors behind attending objectivities of any regenerative farming program.

Abstract

The impacts of climate change on crop productivity and emerging challenges in terms of food security have led to the introduction of a regenerative farming approach in which the regeneration of soil is one of the prime objectives of sustained food production. Currently, compost is considered the key component for soil rejuvenation or, more precisely, soil microbial rejuvenation, as high-quality compost can be considered the most economic source of diverse microflora. Within the scope of the present study, we reviewed different composting methods that were used at large scales for tea estates according to the five-point criteria of end product quality, cost of production, process adoptability potential, post -soil application efficacy and GHG mitigation potential.

In the comparative study, the process adoptability potential was greater in the case of Novcom compost (9.97), which was primarily due to the shortest biodegradation period, non-selectivity of the raw materials and non-dependency on the infrastructural requirements. The compost quality index (CQI) value was also significantly greater in the case of the Novcom compost (CQI: 5.75) than in the Vermi compost (CQI: 2.4) and FYM/Heap compost (CQI: 1.75), which was primarily due to the presence of a very high microbial population (10^{16} cfu per g moist compost; at least 10,000 times greater than that of the other compost) in the Novcom compost.

A 3-year comparative study regarding post soil effectiveness in terms of crop productivity and soil quality development was performed under the FAO-CFC-TBI project in the Maud tea estate, which revealed higher crop productivity (30.75% higher than that of the control and approximately 11% higher than that of the Vermi & FYM/Heap compost applied plots) and a better value cost ratio under the Novcom compost applied plots. The soil quality enrichment was measured through the soil development index (SDI), which revealed more than 55% higher impact in the Novcom compost applied plots than in the other plots, which was due mainly to the increase in the soil microbial population.

Comparative cost analysis on the basis of present material and manday costs revealed that Novcom compost was the most economical (Rs 2345/ton), followed by FYM/Heap compost (Rs 3245/ton) and Vermi compost (Rs 5395/ton), indicating that the Novcom composting method is 60% less expensive than the Vermi composting method.

Most importantly, a comparative study of soil carbon sequestration and GHG mitigation potential under different composting methods evaluated via the IPCC methodology and Century model simulation performed by the EPA revealed that the soil carbon sequestration potential was highest in the case of Novcom compost (152.9 kg CO_2e/ton raw material), followed by FYM/heap compost (69.5 kg CO_2e/ton raw material) and Vermi compost (66 kg CO_2e/ton raw material). Finally, a comparative study of GHG mitigation potential revealed that Novcom compost was much greater than other composting methods, with a value of 508 kg CO_2e/per ton raw material, whereas the nearest value was in the case of Vermi compost, with a value of 277 kg CO_2e/per ton raw material. This was due to the shorter biodegradation period and greater microbial population in the Novcom compost, leading to greater scoring in terms of process efficiency and soil carbon sequestration potential. Thus, for any GHG mitigation program, the adoption of Novcom composting technology could be a natural choice for sustainable soil management.

Keywords: GHG mitigation, compost, process efficiency, soil carbon sequestration, cost

Introduction

Compost is the most crucial component for any sustainable/regenerative farming initiative to improve soil health and support crop production. Compost provides organic matter and restores soil fertility, which is a key goal in regenerative agriculture (Ivanchuk, 2024). However, the scarcity of raw material is a major bottleneck for Indian agriculture (Bera *et al*, 2012; Masthihole, 2011); thus, a qualitative approach towards the utilization of available resources is the most important criterion. Specifically, in a deactivated environment, any ordinary organic manure, compost or rotten organic material does not meet this objective (Seal *et al*, 2012). However, considering the impact of climate change on crop production systems and the degradation of agricultural soil in India (Bhattacharyya *et al*, 2015), the adoption of comprehensive sustainable/regenerative farming is crucial. Thus, we need to identify the composting process/method that can ensure superiority in 5 important criteria: (i) end-product quality, (ii) cost of production, (iii) process adoption potential, (iv) post soil application efficacy and (v) GHG mitigation potential among the present composting process/method used in Indian agriculture to spearhead regenerative farming. The present study compares different composting methods as per the above criteria from published research to review the suitability of major composting processes/methods in the Indian tea sector.

Different composting methods

“In India, cultivation following nature-friendly processes and the application of organic manure/compost is not new. As early as 1000 A.D Surpala (1000 AD) compiled a text called Vrikshayurveda (Vriksha= trees; Ayurveda= science), which described cultivation practices following a natural pathway” (Sadhale, 1996). “The importance of manures in obtaining high crop yields was fully appreciated in ancient India. In Krishi-Parashara (written in 400 BC), crops grown without manure do not yield, and a method of manure preparation has been described” (Sadhale, 1999). “In the Kural (1st century AD), it was written that manuring was more beneficial than ploughing” (Aiyar, 1952).

The first attempt to provide a scientific basis for the composting process and accordingly design composting systems was made from 1924–1926 by Howard and Wad (1931). “The studies were conducted at the Institute of Plant Industry situated at Indore, India, and the process developed there has come to be called the Indore method” (Gajalakshmi and Abbasi, 2008). The drawbacks of the Indore method are that it requires massive inputs of labour in heap construction or the filling of pits, turning, and other maintenance operations. The method also results in significant losses of nitrogen and ammonia, in addition to moisture. To overcome some of these disadvantages, a variant of this method was developed at Bangalore, India, by Acharya in 1939 (Misra and Roy, 2007). “The VAM composting system, which started in the Netherlands in 1932, was a mechanized version of the Indore method” (Gotaas, 1956). “Despite its early popularity and continuous upgrades, its technology became obsolete by 1989” (Haug, 1993). Modifications of the Indore and Bangalore methods have been attempted across the world to speed up the process. The Chinese “high-temperature” composting method (FAO, 1980) is an example. Bin composting represents a simple and “low” technology that can be accomplished with very ordinary and common methods. At the household level, or at small livestock-raising units, composting is usually performed in bins of different sizes and materials ranging from cement bins to emptied cartons (Gajalakshmi and Abbasi, 2008). “NADEP composting is another natural process by which biomass wastes, soil wastes and animal wastes are biologically degraded and decomposed into organic compost, which was developed in India, N.D. Pandharipande” (Kumawat *et al*, 2018). The compost was prepared within 90–120 days within the NADEP tank. The method, which has become quite popular among farmers in Western India,

Rotary drum composters are among the oldest mechanical processing technologies (Fitzpatrick *et al*., 2005), and after many years of being underused, they are back in fashion. Their major attraction lies in their ability to co-compost a mixture of sewage sludge and municipal waste, with an ease that is almost impossible to achieve with other systems. There are other composting processes present in different parts of the world. Some of these systems include in-vessel composting systems (Manyapu *et al,* 2017), the Windrow composting system (Maheshwari, 2014), Passive Windrow Composting (Michel et al, 2022), Turned Windrow Composting (Michel *et al*, 2022), Static piles (ECSs, 2024), pile systems (EPAs, 2023), tunnel composting systems (Koutsoumanis et al, 2020), etc., where the involvement of mechanization is one of the important conditions for composting.

“Currently, Vermi composting is probably the most widely accepted composting method. In this process of conversion, biodegradable matter is converted by earthworms into vermicast. In this process, a major fraction of the nutrients contained in the organic matter are converted to more bioavailable forms” (Gajalakshmi and Abbasi, 2008). The Biodynamic composting method developed by Rudolf Steiner is another widely accepted composting method. Research at Washington State University (WSU) by Dr. Lynn Carpenter-Boggs and Dr. John Reganold revealed that biodynamic compost preparations have a significant effect on composting and composting processes. Compared with the control compost piles inoculated with field soil, the biodynamically treated compost piles had higher temperatures, matured faster, and contained more nitrates than did the control compost piles inoculated with field soil instead of the preparations (Boggs and Lynne 1997).

Novcom composting method, a new biodegradation process, is widely used among the organic tea growers of Darjeeling and Assam because of its simplicity, fast biodegradation, high-quality end products and low economics (Seal *et al*, 2012). “It is an ideal exogenous soil inoculation produced under ‘Novcom composting method’ developed by an Indian scientist Dr. P. Das Biswas; pioneered in sustainable organic tea cultivation in India for the energization of the soil system” (Dolui *et al*, 2014). “Novcom compost can be produced from different types of biodegradable raw material within a short period of 21 days” (Bera *et al*, 2013). The nutrient content of the Novcom compost enables its low rate of application, as maturity and phytotoxicity bioassay tests of the compost indicate its favourable effect on seed germination and plant growth (Seal *et al*, 2017). However, the primary differential criterion of compost from any other available organic nutritional input is its large, naturally generated microbial population, which is on the order of 10^{16} (Bera *et al*, 2017). “When applied to soil, Novcom compost has been found to provide the required plant nutrition and create a favourable environment for rapid microbial growth and proliferation, even in depleted soils” (Seal *et al*, 2016). “Since microbes are the main driving force behind almost every soil function, from soil formation to nutrient dynamics, the large, naturally generated population of microbes helps to rejuvenate soil health in the quickest and most economic manner” (Das Biswas, 2008a; Das Biswas 2008b).

Role of compost in sustainable / regenerative farming initiatives

“The compost regenerates the soil. Healthy soil is living with billions of microorganisms, such as bacteria, fungi and actinomycetes, which are critical for supporting plant growth and ecosystem function. Unlike industrial agriculture, which kills biological life in the soil with chemicals and synthetic fertilizers, compost can help regenerate the natural chemical and biological components of soil, restoring its health” (Anonymous, 2024). “Compost provides organic matter and restores soil fertility, which is a key goal in regenerative agriculture” (Ivanchuk, 2024). Thus, to ensure the objectivity of sustainable/regenerative farming, quality compost is one of the most crucial components for the rejuvenation of soil health. According to Raviv (2005), if compost is applied properly and for a relatively long period (5–10 years, depending upon climatic conditions, soil management and soil type), the original soil fertility can be restored. According to Mays *et al*. (1973) and Smith (1996), the application of compost has positive effects on the structure, porosity, water-holding capacity, compression strength, nutrient content, and organic matter content of the soil. This finding was corroborated by the findings of Dick and McCoy (1993). The addition of compost to soil can affect soil fertility by modifying the physical, chemical, and biological properties of the soil (Fig. 1).

Biologically, compost improves a plant’s nitrogen-absorbing capacity by increasing the mineralization level of the soil and increasing the absorption capacity of natural components from the soil. This is mainly because of the presence of diverse species of bacteria in compost (Sharma *et al*., 1997) in the plant rhizosphere (Alvarez *et al*. 1995). Improvements in crop yield resulting from the application of compost to different crops, e.g., Paddy (Mukhopadhyay *et al*, 2015; Seal *et al*, 2017a), pulses (Seal *et al*, 2017; Hayat *et al*, 2012), vegetables (Seal *et al* 2017b; Bera *et al*, 2014a; Ouédraogo *et al*, 2001), oilseeds (Rasmi *et al*, 2023), horticulture crops (Hampton 2021; Stoffella *et al*, 2014), and tea (Bera *et al*, 2024a, 2024b), have been reported by different groups of researchers in different agro-ecosystems. There are also reports of soil quality improvement by the application of high-quality compost to different soils (Barik *et al*, 2014; Adugna, 2018), including acidic tea soils (Seal *et al*, 2016a; Bera *et al*, 2014; Dolui *et al*, 2013).

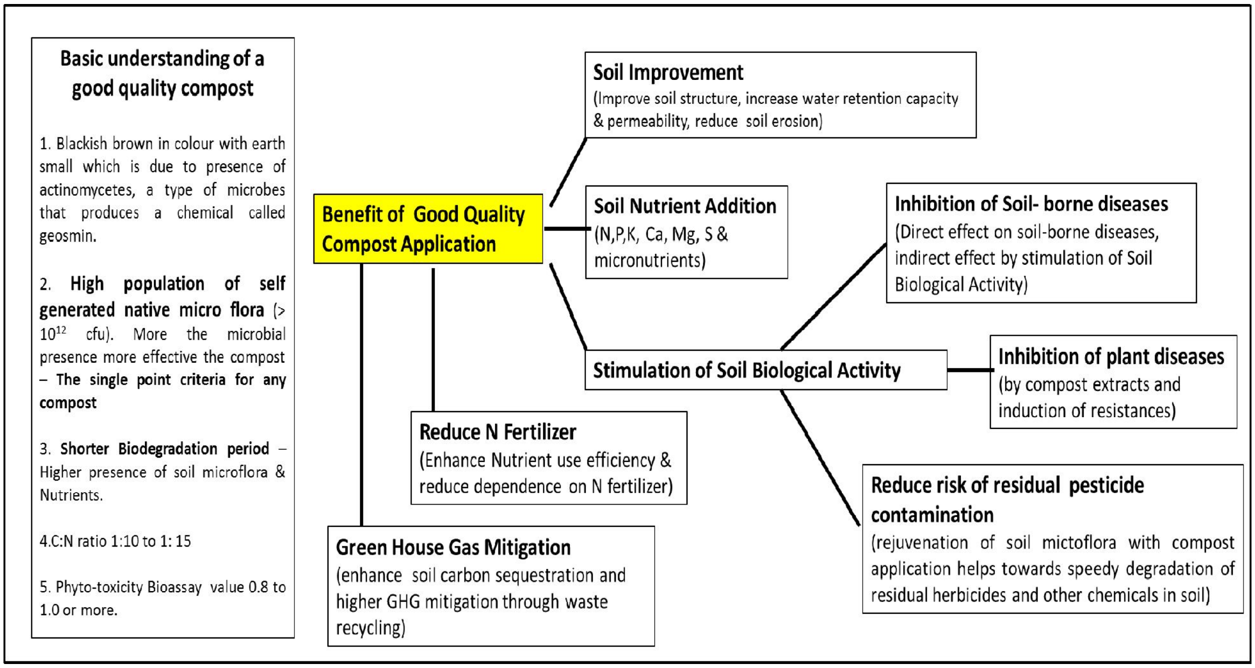

Fig 1 : Benefit of quality compost application in soil

"In addition to improving soil quality and improving crop response, the beneficial impact of compost in many other areas has also been studied. One of the beneficial properties of compost-amended plant growth media is the microbially induced suppression of soil-borne plant pathogens and diseases" (Hoitink and Fahy 1986). "The effectiveness of compost in controlling soil-borne plant diseases, including Fusarium species, is well known" (Hadar and Mandelbaum, 1992; Hoitink *et al*., 1991; Bonanomi *et al*., 2007). In particular, the suppression of diseases caused by Pythium spp. has been well documented (Boehm *et al*., 1993; Chen *et al*., 1988a). "In some studies, Pythium disease suppression has been linked directly to elevated levels of microbial activity caused by compost amendment" (Chen *et al*., 1988a; Chen *et al*., 1988b).

Compost also plays an important role in the breakdown of pesticides in soil. According to Fogarty and Tuovinen (1991), some microorganisms that rely on feedstock for food and energy may co-metabolize pesticides while breaking down adjacent pesticides. High temperatures can also increase the bioavailability of pesticides, increasing the chance of microbial degradation. Lemmon and Pylypiw (1992) studied the persistence of chlorpyrifos, diazinon, isofenphos, and pendimethalin after composting with grass clippings. The authors reported that pesticides were undetectable shortly after application and that they disappeared quickly after composting. Vandervoort (1997) reported similar results, i.e., decreasing concentrations of chlorpyrifos, 2,4-D, isoxaben, triclopyr, clopyralid, and fluprimidol after composting with grass clippings.

"Compost also acts as an excellent amendment to reduce the negative impacts of salinity and sodicity as well as acidic soil properties. Field trials on sodic soils with the application of compost revealed improved biological activity and aided in the breakdown of impeding soil layers, which resulted in increased infiltration of water, consequently increasing the exchange of sodium ions, which were then lost through leaching" (Abrol and Bhumbla, 1979; Hanay *et al.*, 2004). Furthermore, Kahlown and Azam (2003) reported that the adverse effects of irrigation with saline wastewater could be overcome with the application of compost. A study carried out by Slattery *et al.* (2002) on acidic and saline-sodic soils revealed that the addition of compost can increase the soil pH and decrease the Na concentration at greater depths.

Role of composting to attend Sustainable Development Goals (SDGs)

Composting, the process of recycling organic waste into microbial-rich soil amendments, is more than a sustainable waste management practice; it directly contributes to several United Nations Sustainable Development Goals (SDGs). Enhanced composting efforts directly support the task of achieving SDG 2 (Zero hunger) as composting enhances soil fertility and health, leading to increased agricultural productivity and food security. By improving soil quality, composting supports sustainable agriculture (SDG Target 2.4), which is essential for feeding the growing global population and achieving zero hunger. At the same-time by recycling organic waste into compost demonstrate the principle of responsible consumption and production (SDG Target 12.5) as it minimizes waste generation through prevention, reduction, recycling, and reuse, aligning with SDG 12's overarching aim to ensure sustainable consumption and production patterns. Another important role of compost in mitigating climate change by reducing methane emissions from landfills (SDG Target 13.2). Additionally, applying compost to agricultural lands and gardens sequesters carbon in the soil, contributing to the reduction of atmospheric CO2 levels and combating climate change (SDG Target 13.3). In addition, it will also help us partially address numerous other goals (Pic 1), which we might not instantly recognize the importance of until we look at the list of targets each goal carries. For example, SDG 6 (Water and sanitation) has a target (6.4) to increase water use efficiency. Compost, which is known for its ability to improve the water retention capacity of soils, can help us address this target from the agricultural water use efficiency point of view. SDG 11 (Sustainable cities and communities) has a target (11.6) about municipal and other waste management to minimize the adverse impact on the environment. SDG 15 (Life on land) is another example that has a target (15.3) to restore degraded land and soil (Hettiarachchi *et al*, 2020). SDG 17 (Partnerships for the goals) encourages promoting effective public, public-private, and civil society partnerships in one target

(17.17). “Composting is one good example where such partnerships already function very well, especially when the MSW management lies in the public sector and the usage of compost mainly happens in the private sector, while compost is currently made by organizations representing all of the above sectors” (Hettiarachchi *et al*, 2020). However in the process of waste recycling through composting program to attained the goals of regenerative farming as well as objectivities of several SDGs is greatly influenced by the selection of proper composting method.

Pic 1 : Waste recycling through composting method helps to achieve objectivities of 7 SDGs

Brief description of the different composting methods used in tea estates

Preparation of the FYM/aerobic Heap Compost

This type of compost is more common in tea estates. During winter activity, weeds from sections were cleaned and staged as a heap outside the section. Sometime cowdung it applied in the layer, but in most cases, only the green matter was staged, and the height of the heap was not more than 4 to 5 ft. It took 150 -180 days to biodegrade, and sometimes more time was required depending upon the type of raw materials and the frequency of rainfall (Pic 2).

Pic 2 : FYM/ aerobic Heap Compost on the tea estate, Dooars.

Preparation of Vermi compost

Earth worm: A total of 4000–4500 earth worms (Esenia foetida) were required for each layer, which comprises approximately 600–650 kg of raw materials.

Vermi shed and Vermi compost pit: A plastic shed with a bamboo structure was made to protect the Vermi pit from direct sunlight as well as rainfall. A Vermi compost pit measuring 15 ft was prepared. in length, 4 ft. in breadth and 4 ft. in height. The base of the pit was soled with bricks followed by a sand layer. At the top of the sand bed, a thick cow dung slurry was sprayed.

Preparation of Vermi Compost: At a selected upland, chopped green matter and cow dung were stacked on a heap measuring 10 ft. in length, 6 ft. in breadth and 4 ft. in height. Proper watering was performed so that decomposition was initiated. This was maintained for approximately 20-25 days, and frequent watering was performed until the materials were semi-decomposed and the temperature of the heap decreased. The materials were then ready for use in the Vermi pit. The semi-decomposed raw materials were transferred into a Vermi pit, and Vermi was added layerwise at a specific quantity. Watering on a regular basis was performed to keep the Vermi pit moist. The Vermi compost was ready for 40-50 days.

However, most of the time, only cow dung was directly placed in the Vermi pit, and it took approximately 60–75 days to prepare mature compost (Pic 3).

Pic 3 : Vermi compost prepared in tea estates

Preparation of Novcom compost

Novcom solution: Biologically activated and potentized extracts of Doob grass (Cynodon dactylon), Bel (Sida cordifolia L.) and common Basil (Ocimum bascilicum) were used.

Total requirement of Novcom solution: A total of 250 ml of Novcom solution is required for 1 ton of raw material (100 ml on day 1, followed by 75 ml each, on day 7 and day 14).

Preparation of Novcom compost:

Day 1: On a selected upland and flat area, chopped green matter was spread to make a base layer measuring 10 ft. in length, 5 ft. in breadth and 1 ft. in thickness. This layer was sprinkled thoroughly with diluted Novcom solution (5 ml/ltr. thickness), followed by a second layer of chopped green material, once again 1 ft. in thickness. The green matter layer was once again sprinkled with diluted Novcom solution (5 ml/ltr. of water), and the process continued until the total height reached approximately 6 ft. After each layer of green matter was constructed, it was compressed downwards from the top and inwards from the sides for compactness (Pic 4).

Pic 4 : Steps of preparation of Novcom compost (clockwise) at tea estates (day 1).

Day 7: On the 7th day, the compost heap was demolished and churned properly. The material was subsequently laid layer wise, and after each layer, diluted Novcom solution (5 ml/ltr.) was sprinkled thoroughly as on the 1st day. After seven days, the volume of the composting material decreased due to progress in the decomposition process. Hence, once again, the heap height was maintained at approximately 6 ft. The length and breadth of the heap were maintained at 6 ft. x 6 ft., respectively. The heap was once again made compact as described earlier (Pic 5).

Pic 5 : Operations on 7th day: demolishing the heap and again layer wise reconstruction with application of Novcom solution.

Day 14: The same process was repeated as that on day 7, and to maintain the heap height at approximately 6 ft, the length and breadth of the heap were further reduced to 6 ft. x 4 ft. (Pic 6).

Day 21, The composting process was complete, and the compost was ready for use.

Pic 6 : Operations on 14th day: as done on 7th days and the compost was ready in 21 days.

Comparative study of the process adaptability potential under different composting methods

The process convenience and economics play important roles in the large-scale adoption of the composting process. The process adoptability potential was measured through 6 parameters, namely, the infrastructure requirements, biodegradation period (Fig. 2), raw material selectivity, monitoring requirements, process simplicity and sensitivity to external factors. The process adoptability potential score was highest for the Novcom compost (9.97), followed closely by the FYM/heap compost (8.92), whereas the Vermi compost had a very moderate score (5.06) (Fig 3). A higher process adoptability potential score indicates easier processing and greater adoptability by the farmers; thus, a higher score helps with any sustainable extension program.

Table 1: Review of the process adoption potential under different composting methods

Sl No	Parameters	Vermi Compost	FYM Compost	Novcom Compost
Process Efficiency for Composting				
1.	**Requirement of infrastructure**	Yes	No	No
2.	**Biodegradation period**	60 – 75 Days	150– 180 Days	21 Days
3.	**Selectivity of raw materials**	Yes	No	No
4.	**Monitoring requirement.**	High	Low	Medium
5.	**Simplicity in composting process**	Moderately Complex	Simple	Simple
6.	**Sensitivity to external factors**	High	Low	Moderate

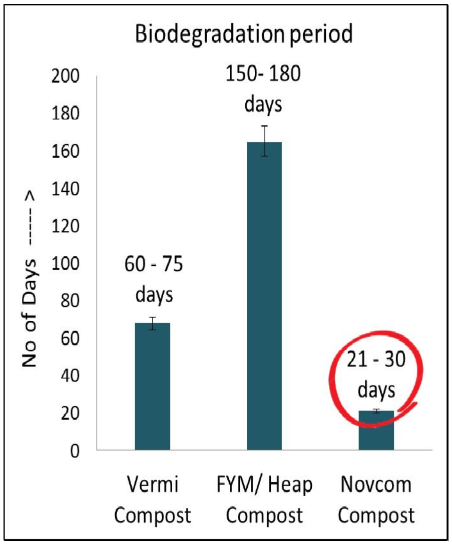

Fig 2 : Biodegradation period under different composting method

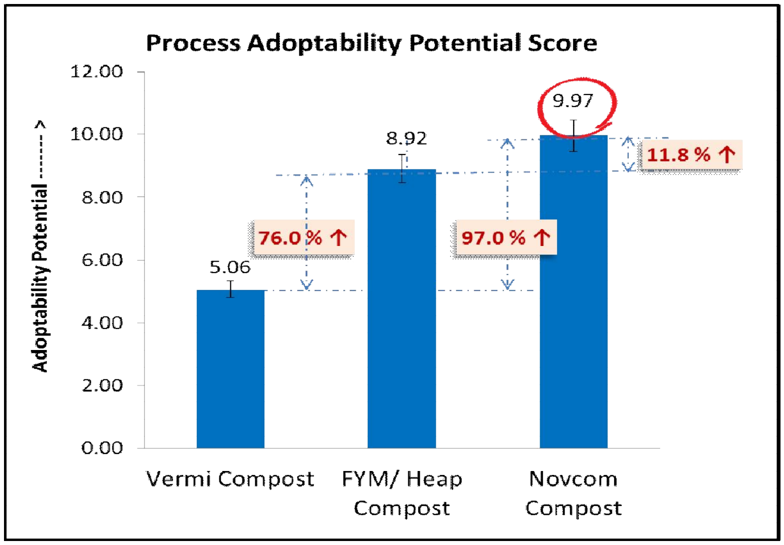

Fig 3 : Process Adoptability Potential Score for different composting method

Review of the end product quality of different composts prepared from green matter and cow dung

For a comparative study of different composts prepared from green matter and cow dung, we sourced databases from a number of published research articles (Bera *et al*, 2013; Dolui *et al*, 2014; Chatterjee *et al*, 2014) and compared them accordingly. The average moisture content of the compost samples ranged from 42 to 61%. pH values of the Novcom compost and heap compost samples were within the stipulated range (7.2 - 8.5) suggested for good-quality and mature compost (Jime`nez and Garcia, 1989), whereas the vermi compost samples were slightly more acidic. Organic carbon content in all the compost samples ranged between 22 and 28%, meeting the criteria for field application (16 to 38) as per the range suggested by the USCC (2002). The compost mineralization index (CMI), expressed as the ash content/oxidizable carbon ratio, varied from 1.8 - 2.6, indicating that all the samples met the standard range (0.79 - 4.38), as suggested by Rekha *et al*. (2005). However, the nutrient content of compost has attracted much interest. The total nitrogen content in the compost samples ranged between 1.4 and 2.2%, which was well within the reference range (1.0 to 2.0%) suggested by Alexander (1994). The highest content of nitrogen (1.8 to 2.2%) obtained in the case of the Novcom compost might indicate greater fixation of atmospheric N within the compost heap under the Novcom composting method (Seal *et al*., 2012). The total phosphate (0.4 to 0.8%) and total potash (0.7 to 1.1%) contents were also higher than the minimum suggested standards (0.6 to 0.9% and 0.2 to 0.5%, respectively) by Alexander (1994). However, on average, the total NPK content in the Novcom compost was 30 and 44% higher than that in the Vermi and indigenous composts, indicating efficient nutrient recycling during the Novcom composting process. The C/N ratio varied from 12:1 to 17:1, indicating that all the compost samples were mature and suitable for soil application.

Table 2: Comparative study of the quality parameters of different composts produced with green matter and cow dung.

Sl. No.	Parameter	Analytical Value		
		Vermi compost	Indigenous compost	Novcom compost
1.	Moisture percent (%)	49.5 -53.2	42.5 -46.5	55.6 – 61.2
2.	pH_{water} (1 : 5)	6.28 – 6.40	7.15 – 7.24	7.35 – 7.85
3.	EC (1 :5) dS/m	1.45 - 1.69	1.54 – 1.65	2.01 – 2.24
4.	Organic carbon (%)	22.1 – 23.2	25.7 – 27.3	26.5 – 28.4
5.	CMI[1]	2.4 – 2.6	2.0 – 2.1	1.8 – 1.9
6.	Total nitrogen (%)	1.2 – 1.7	1.1 – 1.5	1.8 – 2.2
7.	Total phosphorus (%)	0.5 – 0.6	0.4 – 0.5	0.7 – 0.8
8.	Total potassium (%)	0.65 – 0.72	0.65 – 0.74	0.9 – 1.1
9.	C/N ratio	13:1 – 14:1	14:1 – 17:1	12:1 – 14:1
10.	Total bacterial count[2]	(25 -37) x 10^{12}	(10-22) x 10^{12}	(33 – 60) x 10^{16}
11.	Total fungal count[2]	(21 -28) x 10^{10}	(11 -17) x 10^{11}	(18 -29) x 10^{16}
12.	Total actinomycetes count[2]	(11-18) x 10^{10}	(8-10) x 10^{11}	(17 -26) x 10^{14}
13.	CO_2 evolution rate ($mgCO_2$–C/g OM/day)	1.8 – 1.9	1.9 – 2.0	2.5 – 3.2
14.	Seedling emergence (% of control)	85 - 95	90 - 92	95 - 100
15.	Root elongation (% of control)	85 - 92	85 - 95	95 - 105
16.	Germination index (phytotoxicity bioassay)	0.80– 0.85	0.80 – 0.90	0.95 – 1.05
Compost Quality Index (CQI)		**2.3 – 2.5**	**1.7 – 1.8**	**5.5 – 6.0**

[1]CMI : Compost mineralization index; [2] per g of moist soil;

"The microbial status of any compost is one of the most important parameters for judging compost quality because microbes are the driving force behind soil rejuvenation and play a crucial role in crop sustenance by maintaining soil–plant–nutrient dynamics. Microbial population (in the order of 10^{16} c.f.u. to 10^{14} c.f.u. in case of total bacteria, total fungi and total actinomycetes count) in the Novcom compost was significantly greater (at least 10^{3} to 10^{6} c.f.u.) than the populations obtained from other compost samples, as reported by different researchers" (Dolui *et al*, 2014; Mukhopadhyay *et al*, 2021). These findings indicate the potential efficacy of Novcom compost for post soil application and its effectiveness in terms of soil quality development and increased crop support. A comparative study of the stability, maturity and phytotoxicity values indicated that stable compost was free from any phytotoxic effects. However, the germination index value of >1.0 in the case of the Novcom compost (1.02) not only indicated the absence of phytotoxicity (Bera *et al*, 2012) but also confirmed that Novcom compost enhanced rather than impaired germination and root growth (Trautmann & Krasny, 1997).

To classify the quality of the compost produced under different composting method, they were evaluated through compost quality indices (CQI) (Bera *et al.*, 2013b). The CQI was significantly greater in case of the Novcom compost (5.5–6.0), followed by the Vermi compost (2.3–2.5), heap compost/FYM (1.7–1.8) and FYM (1.77).

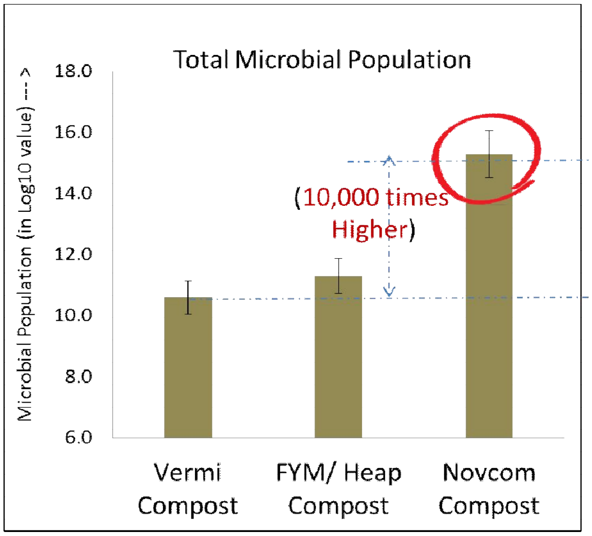

Fig 4 : Microbial population in different compost

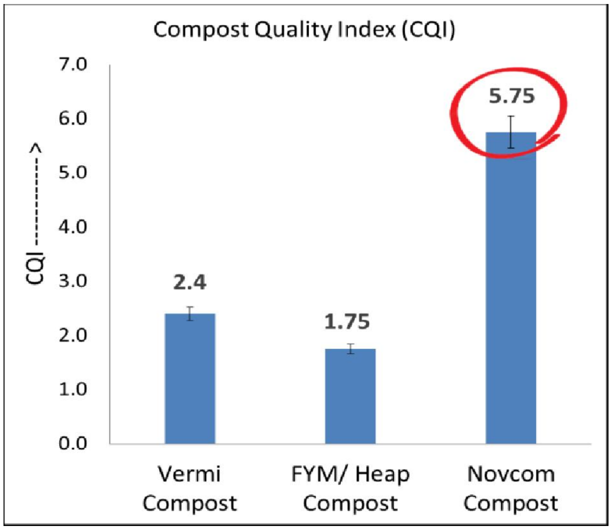

Fig 5 : Comparative Analysis of Compost Quality Index (CQI)

Comparative study of effectivity of different composts towards crop support – A study from FAO-CFC-TBI project at Maud Tea Estate, Assam.

The study at Maud tea estate (Assam), India, under the FAO-CFC-TBI Project (2008-2011) was a lab-to-land evaluation of the quality of organic soil inputs in terms of their relative impact on crop yield and soil rejuvenation. In that study, 7 different soil inputs were used, but in the present review, we only considered the impacts of the Vermi compost, FYM/Heap compost and Novcom compost for comparative study. The crop N requirement was calculated as 60 kg per hectare on the basis of the target yield of 1500 kg of tea, with four percent N required for one kg of tea. The application dose for each soil input was calculated on the basis of its total N and moisture percentage with 80% utilization efficiency. No foliar spray was given except for the Neem & Karanj oil concoction (at a 3:1 ratio, i.e., 3 ltr. neem oil and 1 ltr. karanj oil mixed with 1% soap solution per ha) for pest management in the different treatment plots.

Pic. 7A &7B: Field visit of IFOAM and TRA personnel at Maud T.E. under FAO-CFC-TBI Project.

Table 3: Ranking of different organic soil inputs in terms of crop and cost per hectare in mature tea.

Rank	Organic Soil Input (dose of organic soil inputs)	Yield (kg/ha)	Percent over control	RAE[1]	Cost/ha (Rs.)[2]	VCR[3]
1.	Novcom compost (@ 8 ton/ha)	1500	30.75	100	7,894	8.49
2.	Vermi compost (@ 9.4 ton/ha)	1338	16.23	51.64	57,025	0.92
3.	FYM (@ 8.3 ton/ha)	1321	14.40	46.57	5,400	7.67

[1]RAE: Relative agronomic effectiveness, [2]Cost/ha was calculated on the basis of the 2011 market value. [3]VCR: value cost ratio.

The crop response in terms of tea yield under different treatments was found to be greatest in the Novcom compost applied plots (1500 kg/ha), followed by the plots receiving Vermi compost (1338 kg/ha), closely followed by the FYM applied plots (1321 kg/ha). The crop yield in the Novcom compost-treated plots was 30.8% greater than that in the control plots, whereas it was only 16.23% and 14.40% greater in the Vermi compost and FYM plots, respectively.

In addition to crop response, the cost incurred per hectare is also a determinant factor in the selection of organic soil inputs. The value cost ratio (VCR), which indicates the extra crop grain per rupee invested in organic soil inputs, was high in the case of Novcom compost (8.89), followed by FYM (7.67) and Vermi compost (0.92). The results revealed that in terms of both crop response and economics, Novcom compost was undoubtedly the best option, followed by FYM.

Soil quality development post compost application: A review of findings from the FAO-CFC-TBO Project (2008--2.13) and Inhana Sustainable Tea initiatives (2014--2023)

For a comparative study of soil quality development post compost application, we compared databases from several published research articles (Bera *et al*, 2024; Bera *et al*, 2016; Dolui *et al*, 2014) and reports from the FAO-CFC-TBO Project (2008--2013) and Inhana Sustainable Tea initiatives (2014-2023).

The tea soil was strongly to moderately acidic at reaction pH values ranging from 4.45 to 4.61 (Table 2). After the application of compost for three consecutive years, the pH of the soil samples increased in all the cases. The soil organic carbon and available NPK values also increased with increasing compost application. However, the average increase was greatest in the Novcom compost applied plots, followed by the Vermi compost and heap compost applied plots. However, there was significant difference in soil microbial rejuvenation after compost application. Among the treatment plots, the overall increase in the microbial population was significantly higher in the Novcom compost applied plots than in the control plots, which may be due to the higher presence of self-generated microbial populations in the Novcom compost. As a result, the soil development index was significantly higher for the Novcom compost-treated plots (SDI: 33.2) than for all the other plots receiving different types of compost, which indicated the greater potential of Novcom compost for effective organic soil management in a rapid manner. This finding was also corroborated by the compost quality index, which was highest in the case of the Novcom compost.

Table 4: Comparative study of soil quality post application of different composts.

Soil Quality Parameters	Vermi Compost	Heap Compost/ FYM	Novcom Compost
Physicochemical and fertility parameters			
pH (H_2O)	4.59 (4.54)	4.61 (4.59)	4.72 (4.61)
Organic Carbon (%)	1.18 (1.14)	1.12 (1.09)	1.24 (1.11)
Available N ($kgha^{-1}$)	375.3 (342.8)	406.0 (345.3)	431.4 (393.2)
Available P_2O_5 ($kgha^{-1}$)	30.1 (24.6)	31.9 (23.2)	32.5 (27.8)
Available K_2O ($kgha^{-1}$)	181.9 (174.3)	177.2 (161.3)	178.5 (163.3)
Soil microbial population (per gm moist soil)			
Total bacterial count	$13x10^5$ ($21x10^4$)	$6x10^5$ ($18x10^4$)	$66x10^5$ ($15x10^4$)
Total fungi count	8×10^5 ($17x10^4$)	$7x10^5$ ($9x10^4$)	$32x10^5$ ($11x10^4$)
Total actinomycetes count	$19x10^4$ ($8x10^4$)	$11x10^4$($7x10^4$)	$12x10^5$ ($6x10^4$)

PSB ($\log_{10}$ value)[1]	$22x10^3$ ($11x10^3$)	$18x10^3$ ($9x10^3$)	$18x10^4$ ($12x10^3$)
Soil Quality Development			
Soil Development Index (SDI)	14.9	13.2	33.2

Note: Data in parentheses are the experimental soil analysis data. [1]PSB: Phosphate-solubilizing bacteria.

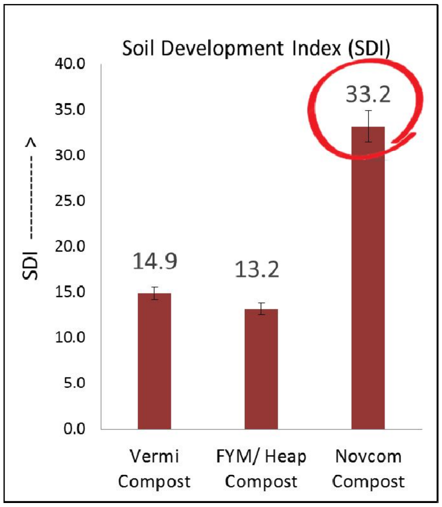

Fig 6: Soil Development Index post application of different compost

Pic 8 : Application of Novcom compost at Maud Tea Estate under FAO-CFC-TBI Project (2009-11)

Comparative cost analysis

Comparative cost analysis was performed on the basis of the average market price of the raw materials in April 2024 and the existing man-day cost in the tea garden. It was found that composting via the Novcom composting method was the most economic, with Rs 2359/- per ton of mature compost, followed by the FYM/Heap composting methods, which cost approximately Rs 3357/- per ton of mature compost. However, the Vermi compost seems to be the most expansive, with Rs 5982/- per ton of mature compost. However, this cost can be increased further if maintenance of infrastructure and the requirement of new earthworms are met within 3 years. The comparative study revealed that the cost of compost produced via the Novcom composting method was 60% lower than that of the Vermi composting method (Fig. 11).

Table 5: Comparative cost analysis of 1 ton of compost produced under different composting methods

Sl No	Parameters	Vermi Compost	FYM Compost	Novcom Compost
1	Cost of green matter collection @ Rs 1.0/kg	667	2857	1250
2	Cost of cowdung @ Rs 1.2/kg	1867	0	375
3	Total raw material cost (Rs)	2533	2857	1625
4	Mandays cost for composting (@Rs 250)	1500	500	500
5	Technology cost (Rs)	0	0	234
6	Infrastructure cost (Rs) #	1949	0	0
7	Total cost of 1 ton compost (Rs)	5982	3357	2359

Infrastructure cost of the Vermi compost includes the cost of the Silpaulin Vermi bed, temporary shed and earthworm on a 3-year project basis

Comparative study of the GHG mitigation potential under different composting methods

Composting is a way to mitigate carbon emissions and help combat climate change in several ways, such as reducing methane emissions by keeping organic materials out of landfills where they breakdown, releasing methane into the atmosphere and improving carbon sequestration; adding compost to soils can increase the amount of carbon sequestered in soils, as well as improve the ability of the soil to store carbon. Numerous studies have shown that adding compost to soil increases soil carbon storage by increasing soil organic matter and increasing plant productivity (Hoover and Rath, 2023). A comparative study of the GHG mitigation potential under different composting methods can be formulated as per the following methodology

$$\text{GHG mitigation under Compost} = \text{GHG saving due to process efficiency}^{\#} + \text{Carbon sequestration in soil (Post soil application)} - \text{GHG emission post soil application} \quad \textbf{---- Eqn 1}$$

#Note: GHG savings due to process efficiency were calculated as per the standard reference value of emissions under composting (Friedrich and Trois, 2011; Hermann *et al.*, 2011; Rogger *et al.*, 2011; Martínez-Blanco *et al.*, 2010; Lou and Nair, 2009; IPCC, 2006) subtracted from the GHG emission value during composting.

As per our reference studies (Jjagwe *et al* 2019; Nigussie *et al*, 2016) and our basic research work (Bera *et al*, 2023; Datta *et al*, 2022; Bera *et al*, 2022; Bera *et al*, 2022a), for the last 3 years, we found that GHG savings due to process efficiency (under the multi-basket approach with

GWP of $CH_{4(24\ years)}$ = 75 and $N_2O_{(100\ years)}$ = 273) under Novcom and Vermi composting methods were 379 and 222 $kgCO_2$/per ton raw material used, respectively. In the case of the FYM/Heap composting method, no process efficiency value was allocated, as it was assumed that GHG emissions during its long biodegradation period and the absence of any specific process facilitated the biodegradation process.

Carbon Sequestration due to application of compost in the Soil : Reference from the latest EPA report (2019), it appears that Century Model is appropriately simulating carbon cycling and storage for all but the passive carbon introduced by compost application. Because passive carbon represents approximately 52 percent of carbon in compost (the midpoint of 45 percent and 60 percent).

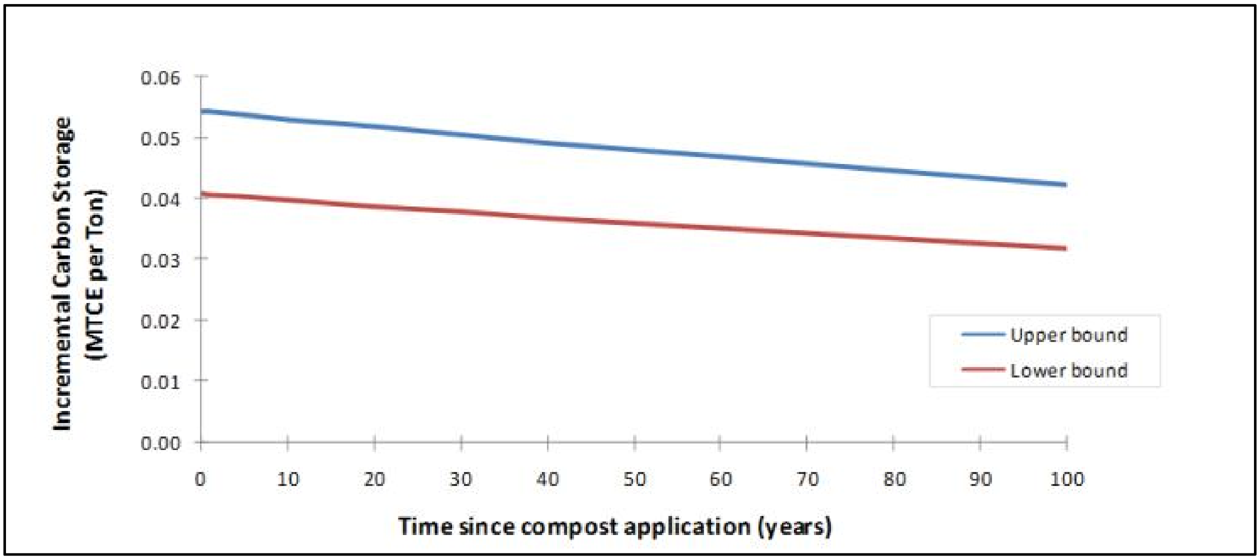

Fig 7 : Carbon Storage Resulting from Humus Effect, Bounding Estimate in WARM Version 15 (Source : EPA 2019; 2020)

In the final calculation as per Waste Reduction Model (WARM), EPA weighed the carbon values from the two carbon storage mechanisms according to the estimated percentage of compost that is passive (assumed to be 52 percent) and then uses the total to estimate the sequestration value associated with composting, as shown in Fig. 7.

Our findings suggest that changes in the soil carbon stock vary widely with (i) climate, (ii) management factors, and most importantly, (iii) soil microbial activity, which is strongly influenced by the above two factors.

Therefore, we propose the following factors to determine the impact of compost on carbon sequestration based on the quality of the compost.

1. Default value: 52%, i.e., when other data are not available, then credit for compost application will be = C_{input} from compost × 0.52 × 44/12.

2. Factor 1: With wet or dry climate = wet (1.1) / moderate wet and dry (1.0) /dry (.9) (climate impact)
3. Factor 2: Microbial value in compost = less than 1010 cfu (0.9) /1010cfu – (1.0) and > 1014cfu (1.1) (Compost Quality Impact)
4. Factor 3: SQI after > SQI initial = (1.1), SQI_{after} = $SQI_{initial}$ (within ± 5%) (1.0) and SQI_{after} < $SQI_{initial}$ (0.9) (Management impact)

Total carbon sequestration/ton compost: Total organic carbon × 0.52 (sequestration factor) × F (cumulative value of 3 factors) × 44/12 ------------ Eqn 2

Currently, according to the IPCC 2006 and 2019 standards, the following formula is used to evaluate GHG emissions from compost post soil application:

GHG emission (kg CO_2e/ ton compost) = $[(F_{ON} \times EF_1) + (F_{ON} \times Frac_{GASM}) \times EF_4 + (F_{ON} \times Frac_{LEACH-H}) \times EF_5] \times (44/28) \times 273$ -------- Eqn 3

Where

F_{ON} = annual amount of compost N applied to soils

EF_1 = emission factor for N_2O emissions from N inputs, kg N_2O–N (kg N input)$^{-1}$

$Frac_{GASM}$ = fraction of applied organic N fertilizer materials (FON) that volatilize as NH_3 and NOx, kg N volatilized (kg of N applied or deposited)$^{-1}$

EF_4 = emission factor for N2O emissions from atmospheric deposition of N on soils and water surfaces, [kg N–N_2O (kg NH_3–N + NO_x–N volatilized)$^{-1}$]

$Frac_{LEACH}$ = fraction of all N added to/mineralized in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff, kg N (kg of N addition)$^{-1}$

EF_5 = emission factor for N_2O emissions from N leaching and runoff, kg N_2O–N (kg N leached and runoff)$^{-1}$.

As per equation 2 above, the total organic carbon sequestration/ton of compost was calculated for different composts on a per ton raw material basis, and it was highest in the case of Novcom compost (152.9 kg/ton raw material). The value was significantly lower for both the Vermi (66 kg/ton raw material) and FYM/Heap (69.5 kg/ton raw material) composts. In the case of vermi compost, the raw material composition, especially the dominance of cow dung, is a limiting factor for high carbon sequestration values. In the case of the FYM/Heap compost, a prolonged biodegradation period caused a higher loss of organic carbon, resulting in a lower carbon sequestration value.

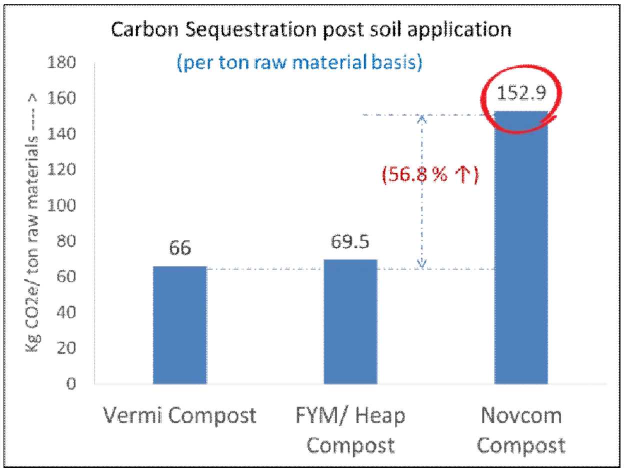

Fig 8: Comparative evaluation of soil carbon sequestration post soil application under different composting method

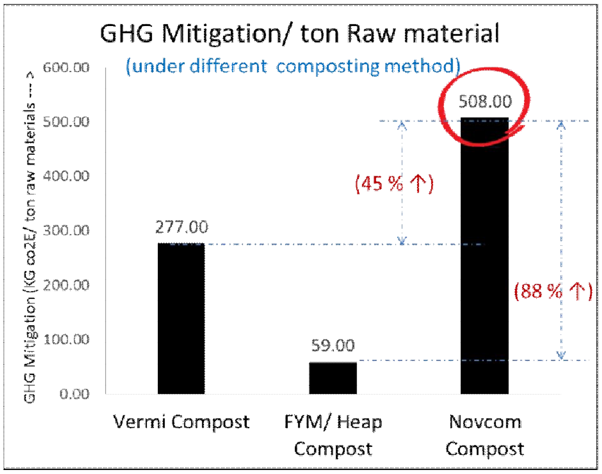

Fig 9 : Comparative evaluation of total GHG mitigation under different composting method

The total GHG mitigation per ton of raw material under the different composting methods was calculated as per the Equation (1) described above. It was highest in the case of Novcom compost (508 kg CO_2e/ton raw materials), followed by vermin compost (277 kg CO_2e/ton raw materials) and FYM/Heap compost (59 kg CO_2e/ton raw materials). The GHG mitigation potential under the Novcom composting method was highest because of its rapid biodegradation process, which reduces the risk of N_2O escape. The presence of a relatively large microbial population under aerobic heap formation eliminates the possibility of methane generation and enhances humification post soil application, leading to increased organic carbon sequestration.

Finally, a spider chart study was done which displayed multivariate data in the form of a two-dimensional chart in which variables are represented on axes starting from the same point. The chart consists of a sequence of equiangular spokes, with each spoke representing one of the variables. The data length of a spoke is proportional to the magnitude of the variable for the data point relative to the maximum magnitude of the variable across all data points. This chart showed the comparative strength/weakness of different composting methods in terms of end product quality, cost of production, process adoptability potential, post soil application efficacy and GHG mitigation potential, and the area of the irregular polygon depicts the cumulative impact of the different composts on addressing the objectivities of any regenerative farming program. The graph (Fig. 10) clearly indicated that there was no match of Novcom compost to address any sustainable/regenerative agricultural initiative.

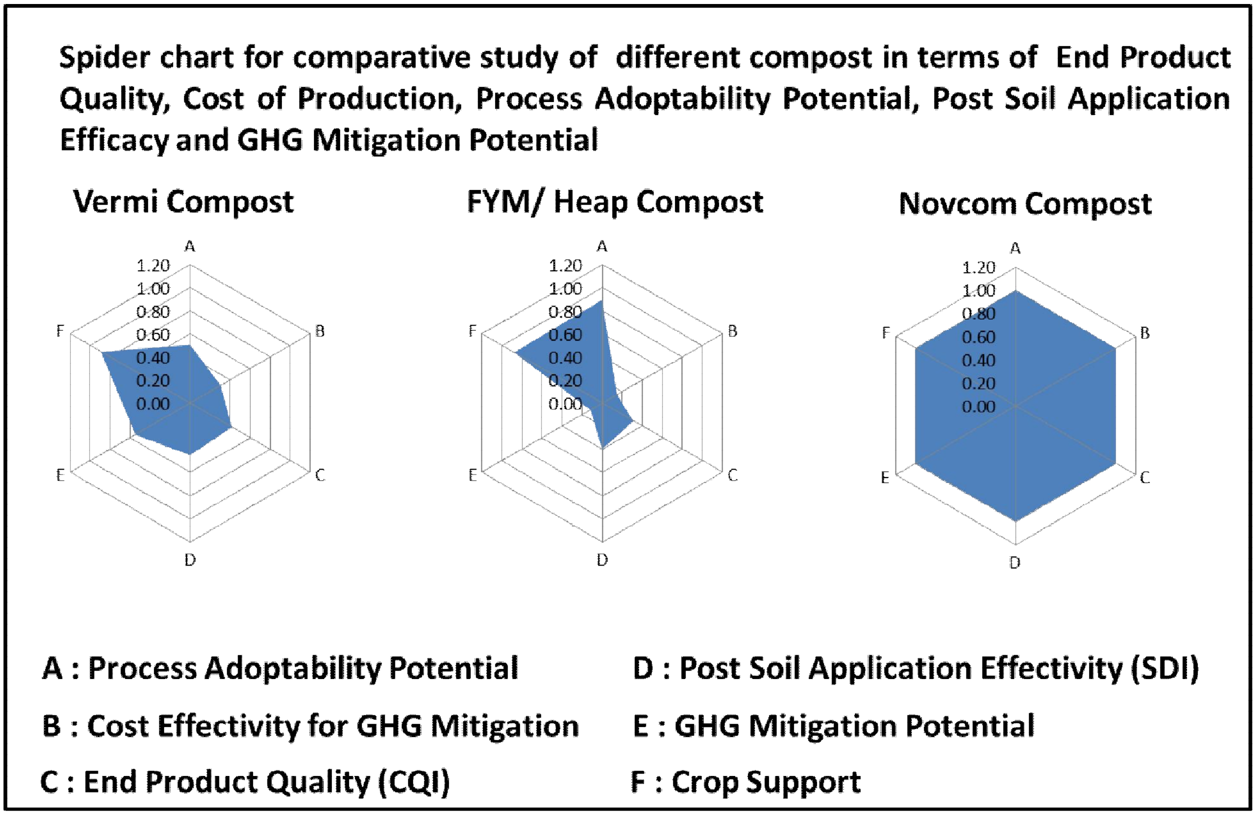

Fig 10: Spider Chart for comparative effectiveness of different compost

Comparative study of 1 ton of GHG mitigation through different composting programs

A comparative analysis of 1 ton of GHG mitigation through different composting programs was performed in the present study via these 3 composting methods in terms of raw material requirements and the cost incurred. These two parameters are the most important factors for decision-making at the management level because the sourcing of raw material is the most challenging issue for most tea estates, especially those that have no added area other than plantations. The reason is that outsourcing raw materials only incurred a relatively high cost. Moreover, the cumulative cost of GHG mitigation through on-farm compost is the most important factor for any GHG mitigation/net zero/regenerative farming program. Present comparative study revealed that the raw material requirement for the mitigation of 1 ton of CO_2 is the lowest for the Novcom compost (1.97 tons), followed by the Vermi compost (3.61 tons). However, most importantly, the cumulative cost to mitigate 1 ton of CO_2e is not only the lowest in the case of the Novcom compost (Rs 2971/-) but also 69% lower than the cost incurred in the case of the Vermi compost (Rs 9708/-).

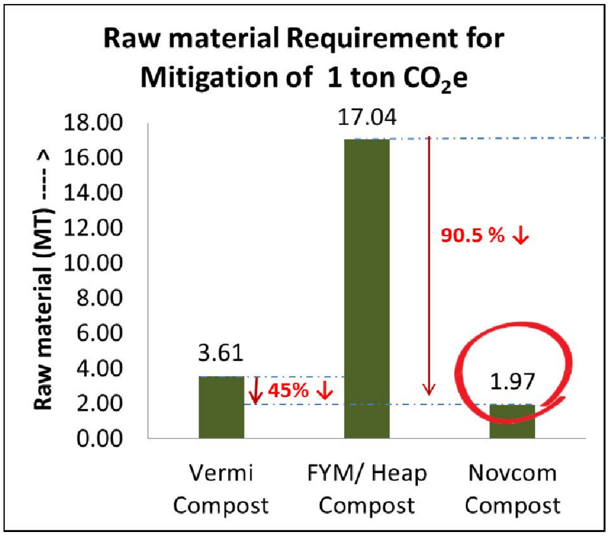

Fig 11 : Raw material requirement for mitigation of 1 ton CO_2e

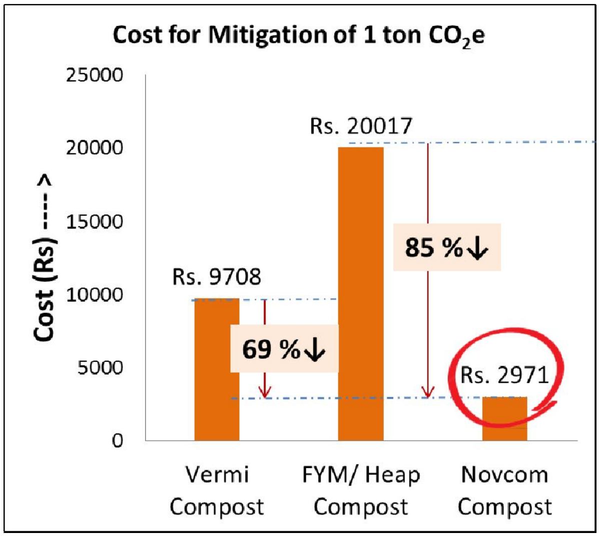

Fig 12 : Cumulative cost incurred for mitigation of 1 ton CO_2e

Conclusion

Regenerative agriculture can play a key role in combating climate change, and high-quality compost is the major weapon for improving soil health, which is the key objective of any sustainable agricultural initiative. A review of different composting methods highlighted the superiority of the Novcom composting method over other methods in terms of end product quality, cost of production, process adoptability potential, post soil application efficacy and GHG mitigation potential. Given the scarcity of raw materials, the availability of mandays and the cost associated with composting programs are major deterrent factors for most tea gardens, this comparative study might help with policy decisions because climate change is a harsh reality, and today or tomorrow, every tea estate must implement a sustainable cultivation program to fight against it. The underlying truth is that it is not a choice but the equation of ether survival or being perished. Thus the present study can serve as an indicative research towards development of a sustainable management program for tea cultivation.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

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

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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