STUDY OF LIFE CYCLE ASSESSMENT AND IMPROVEMENT FOR REDUCING GREENHOUSE GAS EMISSIONS IN TEA SHOOT FIELD PRODUCTION

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ABSTRACT

Tea industry is a crucial agricultural sector in Indonesia, that both contributes to and absorbs greenhouse gas (GHG) emissions. However, limited information exists about GHG emission during these processes. Chemical fertilizers predicted contribute the most portion to GHG emissions in the field, while tea cultivation requires nitrogen in a dominant composition with the most readily available source coming from urea fertilizer. Therefore, the objectives of this study are to calculate the impact of Global Warming Potential (GWP) in tea shoot field production process and to explore methods for reducing GWP through demonstration plots through a combination of bio-organo-mineral fertilizer applications to reduce urea use. The study was conducted in Negarakanaan Tea Plantation (1.350 m asl), West Java Indonesia during 2023 to 2024. The assessment of the life cycle impacts in field activities calculated using the Cool Farm Tool (CFT) software. There was no significant difference in total fresh shoot production between Bio-Organo-mineral combine with 50% Urea (8,246 kg/0.48 ha) and conventional 100% chemical dose fertilizer (8,049 kg/0.48 ha), even Bio-organo-mineral demonstrated a greater improvement in shoot production, particularly during the productive phase of the tea plants (Pruned Years 2 and 3). The GHG's Emission for Bio-organo-mineral were only 55.16 kg CO_2eq per tons compare to conventional plots 125.10 kg CO_2eq per tons and baseline cultivation 186.85 kg CO_2eq per tons. The Bio-organo-mineral treatment improved fertilizer efficiency around 35.98% by reducing the urea dosage by 57.71% and reduced total GHG emissions (CO_2eq) by 55.90% compared to conventional plots.

Key words : Bio-organomineral, GHG emission, Life cycle assessment, Tea shoot production.

INTRODUCTION

Climate change has become a major global challenge, with greenhouse gas (GHG) emissions recognized as the primary driver of global warming. Agricultural activities contribute significantly to atmospheric emissions through fertilizer application, fuel consumption, and land management practices. However, agricultural systems also possess the capacity to sequester carbon, thereby functioning as both emission sources and carbon sinks (IPCC, 2013).

Tea is one of the strategic plantation commodities in Indonesia, contributing substantially to rural livelihoods and national agricultural development. Tea cultivation requires intensive field management throughout its long economic life, including repeated fertilization, weed control, pest management, and harvesting activities. Among these practices, fertilization is considered the dominant source of GHG emissions in tea plantations due to the extensive use of nitrogen fertilizers.

Previous studies reported that nitrogen fertilizers contribute nearly half of total field emissions in tea cultivation systems (Soheili-Fard *et al*., 2014; Zhang *et al*., 2023). Direct nitrous oxide (N2O) emissions originating from urea application considerably increase Global Warming Potential (GWP) during cultivation (IPCC, 2013). Although several studies have evaluated carbon emissions in tea production systems, information regarding GHG emissions and mitigation strategies in Indonesian tea plantations remains scarce (He *et al*., 2023).

Bio-organo-mineral (BIOM) fertilizer has been proposed as an alternative fertilization strategy by integrating organic materials, mineral sources, and beneficial microorganisms to improve nutrient use efficiency while reducing dependence on synthetic fertilizers. Nevertheless, the environmental performance of BIOM under Indonesian tea plantation conditions has not been comprehensively evaluated.

Therefore, this study aimed to quantify GHG emissions associated with tea shoot field production using a Life Cycle Assessment (LCA) approach and to evaluate the effectiveness of BIOM fertilizer in reducing GHG emissions without compromising tea productivity.

MATERIALS AND METHODS

The study was conducted at Nagara Kanaan Tea Plantation, West Java, Indonesia, located at approximately 1,350 m above sea level. Field experiments were carried out from 2023 to 2024 under commercial tea plantation conditions.

The first factor is the use of standard fertilizer and Biom, while the second factor is the pruning level or year of pruning (TP1, TP2, TP3, and TP4). Both factors are designed with three replications, resulting in a total of 24 plots, each measuring 400 m^2. The total area based on the planting year is 0.12 hectares, while the total area per treatment reaches 0.48 hectares (Table 1). The dosage used for standard fertilization refers to the productivity target (Table 2), whereas the dosage for Biom consists of 100% Biom and 50% urea.

Table 1. Plot Detail

Plot Detai	
Total Plot	6 treatments x 4 repetation x 4 YP = 96 plots
Plot Area	400 m2/plot
Total Area/YP	400 m2/plot x 24 plots = 9.600 m2 = 0,96 ha
Total Plot Area	400 m2/plot x 96 plots = 38.400 m2 = 3,84 ha

Table 2. Standard Fertilizer Dosage Tea (Based on Productivity Target)

Research Productivity Target (kg/ha/yr)	Nutrient Dosage (kg/ha/yr)			
	N	P	K	Mg

TP1	1200	96	21	53	16
TP2	1950	156	34	86	26
TP3	3100	248	55	136	41
TP4	1750	140	31	77	23
Average	**2000**	**160**	**35**	**88**	**26**

Life Cycle Assessment (LCA) was conducted using a cradle-to-gate approach focusing exclusively on on-farm activities. System boundaries included fertilizer inputs, pesticide application, harvesting activities, fuel consumption for mechanical harvesting, and transportation of fresh shoots to collection points. The functional unit was defined as one ton of fresh tea shoots produced. Greenhouse gas emissions were expressed as kg CO2-equivalent (CO2-eq) per ton of fresh tea shoots.

GHG emissions were estimated using the Cool Farm Tool (CFT), a web-based assessment platform developed to quantify emissions associated with agricultural production systems. Input parameters included fertilizer types and quantities, pesticide use, fuel consumption, crop yield, and management practices. Fresh shoot yield and emission values were compared between fertilizer treatments. Fertilizer efficiency improvement and emission reduction percentages were calculated based on differences between BIOM and conventional treatments.

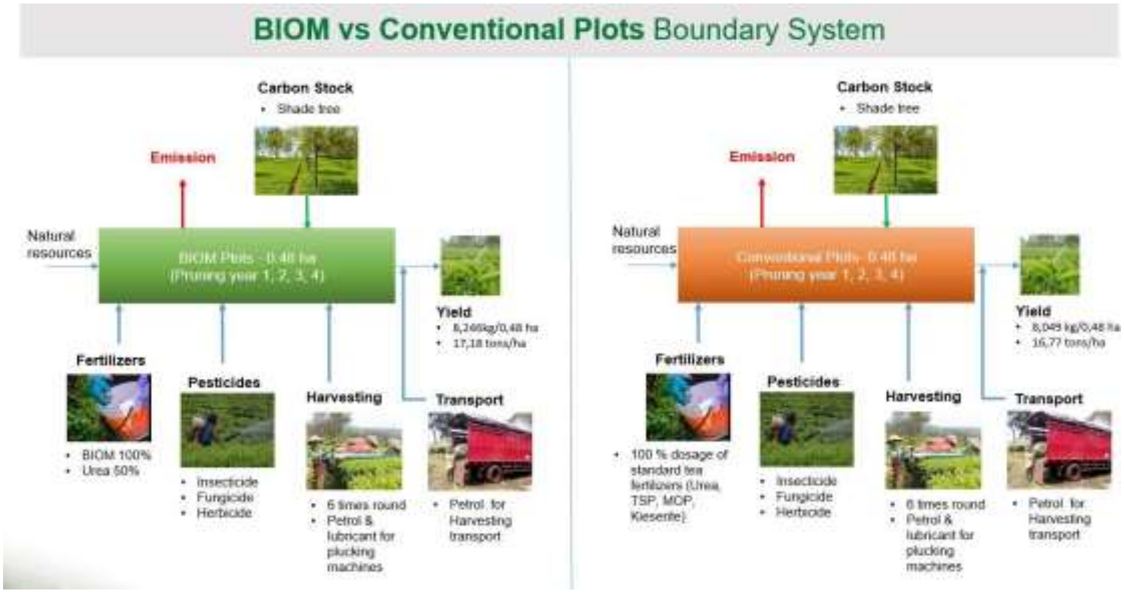

Figure 1. Comparison of the Boundary System for Biom and Conventional Fertilizer Plots The observed parameters include:

1. Shoot production per plot (productivity) per harvest (kg/plot)
2. Greenhouse Gas Emissions from Tea Field Production
3. Techno-economy Analysis of Biom Plot

RESULTS AND DISCUSSION

Fresh shoot production

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Observations of shoot production and quality were made based on the time of harvest in the Negara Kanaan Estate. Shoot plucking is done using a double-operated machine. Plucking process was done 6 times a year from February 2023 – 2024 with range of plucking interval between 60 – 70 days, and the longest plucking intervals is up to 90 days due to el-nino condition as explain in chapter five. The results of the plucking were then weighed to determine the production of fresh shoots in each plot and accumulated from 6 times of plucking, expressed by kg/400 m2. Estimated shoot production per hectare is calculated by extrapolating the accumulated production in one year from the plot area to the area per hectare (kg/ha). The improvement of fresh shoot growth was determined by averaging the increase in fresh production each plot from one plucking to the next and expressed by percentage (%). In addition to the production components, the quality of the shoots is also analyzed by calculating the percentage (%) of peko shoots in each production process. The formation of peko shoots is the formation of shoots that are actively growing.

Fresh shoot production obtained under BIOM treatment was comparable to that achieved under conventional fertilization. Total fresh shoot yield reached 8,246 kg per 0.48 ha in BIOM plots, slightly higher than the 8,049 kg per 0.48 ha recorded in conventional plots.

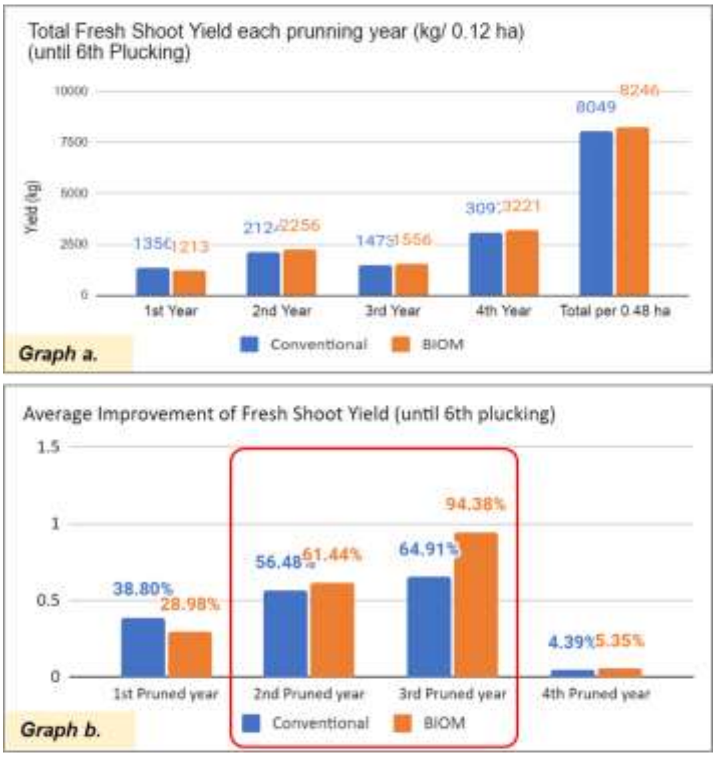

Figure 2. Total fresh shoot yield a year each pruning year (a) and average improvementof fresh shoot production until 6th plucking (b)

Table. 3. Fresh shoot, Shoot Improvement and Peko Percentage of BIOM + 50% Urea vs Conventional Fertilizers

Treatment	Fresh Shoot per plots (kg/400 sqm)	Shoot Improvement (%)	Pecco Percentage (%)

Prune Year			
1st Pruned year	428 a	0.40 b	0.52 a
2nd Pruned year	730 b	0.64 b	0.69 b
3rd Pruned year	504 a	0.94 c	0.53 a
4th Pruned year	1053 c	0.18 a	0.22 c
Fertilizers			
Conventional	111	0.49	0.47
BIOM + 50% Urea	113	0.59	0.51

In the tea plant cultivation cycle, the 2nd and 3rd pruning years are the productive phase, while the 4th pruning year is a phase of decreasing production so tea plants require pruning to rejuvenate shoots and vegetative growth. In this productive phase, continuous availability of nutrients is very necessary, because production is carried out continuously. The composition of bacteria, organic materials, minerals and combined with half the dose of urea fertilizer, is thought to be able to provide continuity of nutrients for a long period of time and continuously. The nutrient fixing and solubilizing bacteria in Biom release nutrients bound in the soil to become available for plants, while organic materials provide improvements to the physical, biological properties and cation exchange capacity of the soil.

However, in Pruned Year-1, the conventional fertilizer showed higher improvement of shoot compared to Biom fertilizer. This was expected due to this stage requires the absorption of nutrients that are quickly available. In the 1st pruning year, the tea plant needs to build a branch, and frame, in order to make a good foundation of plucking point, therefore a quick supply of nutrition is needed. In the 4th pruned year, both Biom and conventional treatment did not show a significant improvement in shoot production due to the physiological phase of tea, normally 4th pruning year is a phase of decreasing production so tea plants require pruning to rejuvenate shoots and vegetative growth.

The results indicate that reducing urea application by 50% through BIOM substitution did not adversely affect tea productivity. Furthermore, BIOM treatment showed greater yield improvement during the productive phase of tea plants, particularly during the second and third pruning years. The presence of organic matter and functional microorganisms in BIOM likely enhanced nutrient availability and improved nutrient uptake efficiency.

Greenhouse gas emissions from tea field production

The results of the emission calculations for the Biom plot and conventional plot based on the CFT are presented in Figure 3,4 and 5. The total greenhouse gas emissions produced including the use of fertilizers, energy, transportation, and other inputs from tea plant production on the Biom plot per ton of tea product produced are 55.16 kg CO_2e (Figure 3). With a final product yield of 8.25 tons, this figure demonstrates the efficiency of production in managing emissions per ton of product.

The conventional plot (Figure 4) standard fertilization practices are used as a reference for fertilization activities in tea plantations, particularly in Indonesia. According to the CFT results,the total emissions from the entire tea production in the conventional plot amount to are

125.10 kg CO_2e, per ton fresh shoots with a final production yield of around 8.05 tons. From a comparison of calculations using CFT (Figure 5), it can be seen that the BIOM plot combined with 50% Urea can reduce CO2 emissions in the field by 55.90% compared to conventional plots, namely fertilization with standard tea cultivation.

Figure 3. Emission Analysis Results based on CFT for the Biom + 50% Urea Plot

Figure 4. Comparison CO2 emission BIOM vs conventional plots

Table 4. CFT Final Analysis of BIOM vs Conventional Plots

Sources	Total Kg CO2eq per ton			
	Conventional	%	BIOM	%
Chemical Fertilizers	121.32	96.99%	25.89	46.94%
Biom Material			25.38	46.01%
Crop protection	1.7	1.36%	1.66	3.01%

Carbon Stock	-14.46	-11.56%	-14.11	-25.58%
Energy and Transport	16.53	13.21%	16.34	29.62%
Total	125.09		55.16	

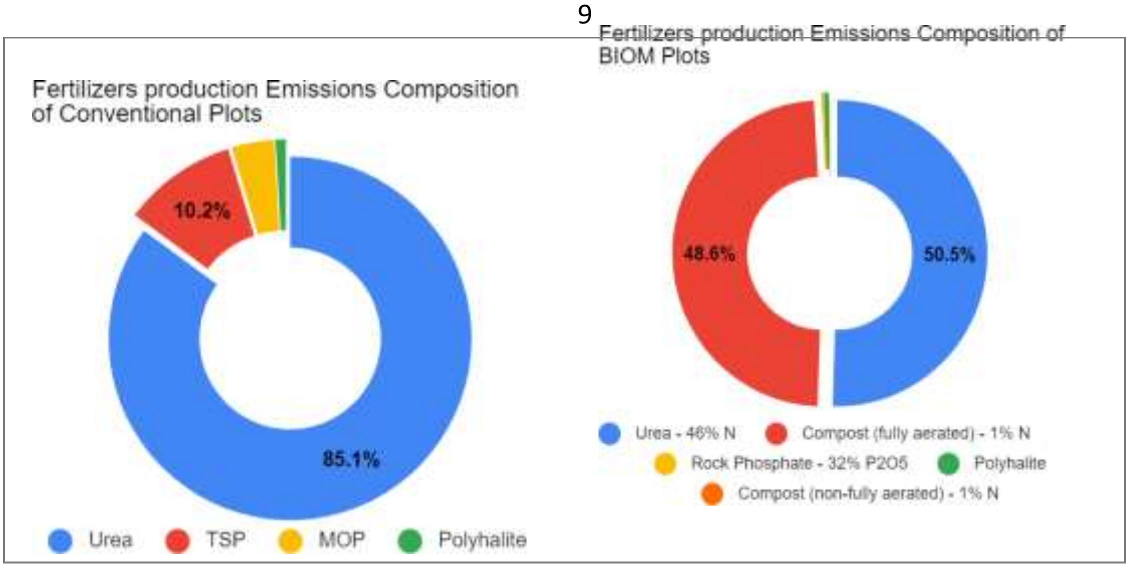

Figure 5. Fertilizer emission composition of conventional and Biom Plots

Sources of emissions in the experimental plot dominantly come from fertilizer materials and fertilization activities, followed by few number of gasoline fuel energy for the process of plucking and transporting shoots and pesticides application. At the conventional plots (Figure 17), Urea dominates the composition of emission hotspots from fertilizer materials at 85.1%, followed by TSP 10.2% and MOP 3.8%, meanwhile in the BIOM plot, the emission hotspot composition from fertilizer material production comes from 50.5% Urea and 48.6% organic material from the BIOM fertilizer composition.

LCA analysis using the Cool Farm Tool revealed substantial differences in GHG emissions among treatments. BIOM treatment produced the lowest emissions, amounting to only 55.16 kg CO2-eq ton−1 fresh shoots. In contrast, conventional fertilization generated 125.10 kg CO2-eq ton−1, whereas baseline cultivation reached 186.85 kg CO2-eq ton−1. The lower emissions observed in BIOM plots were primarily associated with reduced synthetic nitrogen fertilizer application. Nitrogen fertilizers, particularly urea, are recognized as major contributors to direct N2O emissions in agricultural soils (IPCC, 2013). Consequently, lowering urea inputs effectively decreased total GWP. The findings are consistent with previous studies reporting that synthetic nitrogen fertilization represents the largest emission hotspot in tea production systems (Soheili-Fard *et al.*, 2014; Zhang *et al.*, 2023). Therefore, optimizing nitrogen management is essential for reducing carbon footprints in tea plantations. Techno-economy Analysis of Biom Plot

Techno-economic analysis and carbon emissions as an impact of global warming were carried out to compare Biom and conventional treatments, to find out how much efficiency there is in using fertilizer, reducing urea, and reducing carbon emissions. Techno-economic analysis can be presented in the following table. Economic analysis is carried out by calculating the cost of raw materials for fertilizer required, excluding fertilizer labor costs, and harvest. Labor costs for fertilization and harvesting or other fixed costs are considered the same between treatments or ceteris paribus.

Table 5. Techno Economy & GWP analysis of BIOM

Component*	Fertilizers Type (0,48 ha)	
	Conventional	BIOM
Fresh shoot (kg)**	8246.30	8049.40
Total dossage (70% apps)		
Biom (Kg)	246.00	
Urea (Kg) -46% N	70.50	166.70
TSP (Kg) - 46% P2O5		36.60
KCl (Kg) - 60% K2O		70.50
Kieserit (Kg) - 27% MgO		46.90
Fertilizer cost		
Biom (Rp)	1,476,000	
N (urea) (Rp)	634,500	1,500,300
P (TSP) (Rp)		494,100
K (KCl) (Rp)		754,350
Mg (Kiserit) (Rp)		469,000
Total Fertilizer cost (Rp)	2,110,500	3,217,750
Fertilizer cost per kg shoot (Rp/kg)	256	400
Cost Efisiensi (%)	35.98%	
Total LCA by CFT (Kg CO2-eq/tons)	125.09	55.16
Total GWP reduce by CFT (%)	-55.90%	
Total LCA by OLCA (Kg CO2-eq/tons)	213.66	111.97
Total GWP reduce by OLCA (%)	-47.59%	
Urea reducing (%)	57.71%	

Application of BIOM significantly improved fertilizer use efficiency. BIOM treatment reduced urea dosage by 57.71% while increasing fertilizer efficiency by 35.98%. Despite lower synthetic fertilizer inputs, fresh shoot production remained comparable with conventional practice. Overall, BIOM reduced total GHG emissions by 55.90% compared with conventional fertilization. These results demonstrate that integrating organic materials, mineral components, and beneficial microorganisms can simultaneously improve nutrient utilization and mitigate climate impacts (IPCC, 2013). The environmental benefits of BIOM are particularly relevant for sustainable tea production, considering increasing global concerns regarding carbon footprints in agricultural commodities. Adoption of BIOM technology could support low-carbon tea production and contribute to national climate mitigation targets.

CONCLUSION

In on-farm activities Based on the CFT testing results, the BIOM treatment produced the lowest emissions compared to other treatments. The emissions for the BIOM plot were only 55.16 kg CO_2eq per tonss of tea shoots in CFT analysis. In contrast, the highest emissions were recorded in the baseline 2019-2021, with emissions reaching 186.85 kg CO_2eq in CFT analysis. The BIOM treatment demonstrated a 35.98% improvement in fertilizer efficiency by reducing the urea dosage by 57.71%, leading to a more efficient use of fertilizers. The CFT method showed that the BIOM treatment reduced total GHG emissions (CO_2eq) by 55.90% compared to conventional plots. Similarly, the Open LCA method indicated a reduction of 47.59% in GHG emissions for the BIOM treatment. This approach also increased fertilization efficiency without significantly affecting fresh leaf production, maintaining production levels similar to conventional chemical fertilization.

Bio-organo-mineral fertilizer combined with 50% urea successfully maintained tea shoot productivity while substantially reducing greenhouse gas emissions in tea field production. BIOM treatment generated the lowest GHG emissions, reduced urea application by more than half, and improved fertilizer efficiency compared with conventional fertilization. Therefore, BIOM application represents a promising strategy for developing sustainable and low-carbon tea production systems in Indonesia.

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