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Research article

Carbon Footprint Assessment Using Synthetic Fertilizer and Liquid Organic Biofertilizer in Cassava Cultivation to Promote Good Cultivation Practices and Prevent Greenhouse Gas Emissions

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Abstract: Typically, agricultural crop production contributes to greenhouse gas (GHG) emissions, especially the use of synthetic fertilizers and, less frequently, the application of organic fertilizers. Synthetic fertilizers have both positive and deleterious effects on the natural ecosystem. The primary purpose of this study was to evaluate cassava root yields harvested using two different cultivation methods: synthetic fertilizers and liquid organic biofertilizers. We investigated the amount of raw material fertilizers required for each cultivation method to evaluate the effects of global warming potential (GWP) on cassava cultivation methods in northeastern Thailand. The system boundary was defined from cradle to farm gate, encompassing cultivation and progressing through to harvest, using life cycle assessment (LCA). The input and output data were analyzed to assess the potential impacts of global warming over 100 years. The experiments found that 1000 kg of cassava root product harvested with synthetic fertilizer released the most GHGs, 51.83 kg CO_2eq/1000 kg. This was 10 times that of the experimental plot using a liquid organic biofertilizer at 2.74 kg CO_2eq/1000 kg. Therefore, as farmers face challenges ranging from drought to low yields, and as agriculture becomes less predictable in the face of a changing climate, it is essential to help farmers transition to practices that increase resilience and dramatically decrease their reliance on fossil-fuel-based chemicals. To develop guidelines for reducing GHG emissions in cultivation, the focus should be on farmers' cultivation activities, especially fertilizer application.

Keywords: Carbon footprint; Greenhouse gas emissions; Synthetic fertilizer; Liquid organic biofertilizer; Cassava cultivation

1. Introduction

Fertilizers are a crucial component of global food production, essential for sustaining our growing population [1]. However, fertilizers can also generate greenhouse gas (GHG) emissions, with potential nutrient losses to the environment [2]. Agriculture, as a sector, is responsible for non-CO_2 emissions generated by crop cultivation and livestock activities. CO_2 emissions do not primarily come from changing forests, but rather from burning fossil fuels and volcanic eruptions. Another factor that affects global warming is the cultivation of agricultural products [3]. The agricultural sector's use of synthetic nitrogen (N) to accelerate growth and increase crop yields is considered unsustainable. In 2018, the production of synthetic nitrogen fertilizer released approximately 1.13 billion tons of greenhouse gases, accounting for 10.6% of all greenhouse gas emissions. This figure comprised around 2.1% from farming and 38.8% from fertilizer production [4]. In 2019, Thailand emitted 373 million tons of carbon dioxide equivalents. Most are produced by the energy and transportation sector (261 million tons, 70%), followed by the agricultural sector (57 million tons, 15%), the industrial process and product use sector (38 million tons, 10%), and the waste sector (17 million tons, 5%). The most common source of GHG emissions in the agricultural sector (13 million tons, 22%) is the use of fertilizer and lime in plantation plots [5]. Chemical fertilizers are essential for agricultural development when soils lack the nutritional balance required for plants [6]. However, the continuous use of chemical fertilizers has negatively impacted the physicochemical and biological properties of soils. Using biofertilizer products is considered an alternative for reducing the environmental impact of chemical fertilizers [7]. Organic fertilizers are fertilizers that come from living things, both plants and animals, that have undergone processing or have been piled up until they have completely decayed. These fertilizers are in a form that plants can use, such as decayed leaves, compost, various animal manures, bone meal, bean meal, green manure, and municipal waste [8]. Liquid biofertilizers contain live microorganisms that improve soil properties and increase plant growth and yield. Liquid biofertilizers can be applied to various crops and are often more effective than chemical fertilizers; they help reduce the need for chemicals and enhance their effectiveness by promoting improved plant growth [9]. The use of biofertilizers is a crucial component of integrated nutrient management, as they are cost-effective and serve as a supplement to chemical fertilizers for sustainable agriculture [10]. Finally, further research is necessary to overcome the limitations of improved climate adaptation and develop effective liquid organic biofertilizers. We may utilize a superior liquid biofertilizer with a longer shelf life and lower cost, or utilize existing machinery for large-scale applications. In a study that looks at costs and benefits, it's important to assess how safe and effective liquid biofertilizers are over time and to work with different groups to see if they can be used successfully, taking into account the specific location, type of crop, soil type, and weather conditions [11]. Fertilizing with solid organic fertilizers before planting can accumulate and significantly increase N_2O emissions [12]. However, multiple applications of liquid organic biofertilizers do not affect N_2O emissions. Applying solid organic fertilizer before planting can lead to excessive emissions compared to using liquid organic fertilizer due to its higher C/N ratio, which results in increased CO_2 emissions.

Therefore, farmers should consider using liquid organic fertilizers in multiple applications to reduce GHG emissions from their soil plots and achieve high yields. Using liquid organic fertilizer multiple times can reduce GHG emissions. The type of fertilizer and application method can affect N_2O emissions, while soil temperature and water content also influence these emissions. [13]. Cassava is a field crop that produces tubers and is one of the most important economic crops in Thailand, which is the world's top exporter [14]. The cassava production in 2024 is expected to utilize 9.049 million rai (1 rai = 1,600 m^2) and realize production of 27.941 million tons at an average yield of 3.088 tons per rai compared to 2023 with a harvest area of 9.350 million rai, a yield of 30.732 million tons, and an average yield of 3.287 tons per rai. The cultivated area, production, and yield per unit area decreased by 3.22%, 9.08%, and 6.05%, respectively. The drop is due to the drought crisis and the deterioration of soil quality resulting from cultivation. Thailand imported 4,103,668 tons of chemical fertilizers in 2023 as raw materials, primarily for agricultural cultivation. Chemical fertilizers used in cassava cultivation account for 5% of the total quantity of imported synthetic fertilizers [15]. For cassava cultivation in areas with sandy loam or sandy soil, farmers typically use a fertilizer formula of 15-15-15 at a rate of 100 kg per 1,600 m^2, applying it once after planting when the cassava is 1–3 months old [16]. In general, the carbon footprint for 15-15-15 chemical fertilizers is 1.5083 kg CO_2eq/kg [17]. Inorganic fertilizer is defined as a type of fertilizer composed of inorganic substances. Derived from natural and synthetic inorganic fertilizers, natural inorganic fertilizers are those that contain inorganic substances that occur naturally, such as ground phosphate rock and mineral sylvite (potassium chloride, KCl, a type of potassium fertilizer). Chemical methods produce synthetic inorganic fertilizers, including ammonium sulfate, triple superphosphate, and phosphates. Inorganic fertilizers can be synthetic chemical fertilizers or natural fertilizers [18]. The fertilizers imported into Thailand include ammonium sulfate (formula 21-0-0), urea (formula 46-0-0), potassium chloride (0-0-60), and diammonium phosphate (formula 18-46-0) [19]. Table 1 displays the quantity of synthetic fertilizers Thailand imported between 2018 and 2022. Thailand's cassava cultivation from 2018 to 2022 utilized a substantial amount of synthetic fertilizer, as indicated in Table 2.

Table 1. Quantity of chemical fertilizer imports in Thailand in 2018–2022.

Mono fertilizers/ compound fertilizers	**Volume (%)**	**Mixed fertilizers/ various fertilizer**	**Volume (%)**
Urea 46-0-0	42	16-20-0	7
21-0-0	4	15-15-15	7
0-0-60	14	13-13-21	16
18-46-0	19	16-16-8	1
Total	79		31

Source: Office of Agricultural Economics, Thailand (OAE) [15]

Thailand aims to achieve carbon neutrality by 2050 and net-zero GHG emissions by 2065. Chemical fertilizer production is a heavy industry with a high impact on carbon emissions. This industry may need to adapt quickly because it is at risk of being subjected to a carbon tax in many countries; in particular, the European Union began collecting carbon taxes in 2023 [20]. Urea fertilizer is a synthetic organic substance that contains nitrogen (N) as a component in a very high ratio, 46% by weight. Urea fertilizer is a standard chemical fertilizer. Most importantly, the fertilizer formula for urea is 46-0-0 because it has the highest proportion of nitrogen. Therefore, it serves as a primary source of nitrogen fertilization. Plants use urea fertilizer 46-0-0 as their primary nutrient. Early planting stages necessitate a rapid acceleration of plant growth. This results in the plant developing long stems, bushy leaves, and large, dark green leaves, as well as good weight. Additionally, the production of urea as a nitrogen (N) fertilizer has a greenhouse gas impact of 3.3036 kg CO_2eq per 1 kg of urea fertilizer (TGO) [17]. Ammonium sulfate is a type of nitrogen fertilizer commonly used in Thailand. The chemical formula is $(NH_4)_2SO_4$, and the fertilizer formula is 21-0-0, consisting of approximately 21% nitrogen (N) and approximately 23% sulfur (S). Ammonium sulfate is a simple nitrogen fertilizer that increases nitrogen levels in the soil and serves as an important nutrient for nourishing plant leaves. Making ammonium sulfate as a P_2O_5 fertilizer creates a greenhouse effect that is equal to 1.5716 kg of CO_2 for every 1 kg of AMS fertilizer produced (TGO) [17].

Potassium chloride fertilizer formula 0-0-60 contains 0% nitrogen, 0% beneficial phosphate, and 60% water-soluble potassium. Its duties and importance to plants are as follows: 1) promote root growth, enabling better water absorption in the roots, and 2) create good-quality fruit pulp. Making potassium chloride as a K_2O fertilizer produces greenhouse gases equivalent to 0.4974 kg of CO_2 for every 1 kg of K_2O fertilizer (TGO) [17]. Fertilizer 15-15-15 is a chemical fertilizer formula containing the same nutrients as nitrogen (N), phosphorus (P), and potassium (K) at 15% or in an NPK ratio of 1:1:1, which is suitable for general plant maintenance. It is commonly used on mature fruit trees and perennials. During the period after the harvest, its distinctive feature is that it contains all three main nutrients that plants need in equal amounts. Therefore, it nourishes every part of the plant simultaneously. It did not, however, highlight any one area. The production of GHG from 1 kg of fertilizer 15-15-15 has an impact equal to 1.5083 kg CO_2eq (TGO) [17].

Table 2. Quantity of chemical fertilizer imports in Thailand in 2018–2022.

Planting Harvest Year	**Chemical fertilizer (kg/1600 m^2)**	**Planting area (m^2)**	**Average yield (kg/1600 m^2)**
2018	41	12,400,667,200	3,499
2019	41	12,005,803,200	3,527
2020	43	12,754,060,800	3,586
2021	42	13,019,736,000	3,252
2022	43	15,140,667,200	3,372

Source: Office of Agricultural Economics, Thailand (OAE) [15]

People also view the agricultural sector as contributing to global warming, as harvesting rice and livestock releases methane gas. Moreover, nitrous oxide released from fertilizer and livestock urine contributes more to the GHG climate than carbon dioxide, although in smaller amounts. However, the agricultural system that creates GHGs is not small-scale farming. However, industrial agriculture, which relies on monocultural crops such as rice, corn, sugarcane, cassava, and rubber, as well as livestock, requires nitrogen fertilizers, pesticides, and fossil fuel-powered machinery. This type of industrial agriculture creates enormous ecological impacts, destroying soil, water, and forests that have the potential to absorb carbon dioxide. Additionally, the long-distance food transportation system relies on freezing and transport methods. When the food reaches urban consumers, a significant amount of food waste contributes to greenhouse gas emissions [21].

Agricultural cultivation practices for cassava provide accurate information about effective cultivation methods, covering all stages from planting to maintenance and harvesting, as well as the appropriate planting locations. If the area where cassava is planted or the water source is close to places that may be polluted with heavy metals and pesticides, such as near factories or areas that use many chemicals, then soil and water tests should be conducted to detect harmful substances. A record of the land's history should be kept for each plot, including details such as the farmers' names, addresses, the plot keeper's name (if applicable), their address, the size of the area, the location of the plot, the types and varieties of cassava, and any other relevant information. Soil preparation. Suppose cassava is grown in the same place for many consecutive years. In that case, the soil should be improved to maintain long-term production levels by adding manure compost from cassava peels or various legumes that can be planted in rotation to nourish the soil. Weeds should be eliminated before planting. The weeds should be plowed under in the plot to be planted, and they should be left for 20–30 days to allow the weeds to ferment and decompose into fertilizer in the soil. Using reduced tillage in combination with crop residue retention can increase soil organic carbon and reduce carbon footprints [22]. The plot should be plowed another 1–2 times as appropriate, and cassava can be planted while the soil is still moist.

Prepare the cuttings. You can cut fresh cassava cuttings that are 10–12 months old, but don't leave them for more than 15 days. They should be cut to a length of about 20 cm and have at least five buds. To protect against fungi and insects, dip the cuttings in a chemical solution. Cassava is planted in straight rows for ease of maintenance and weed control, with a row distance of 1.20 meters, a plant distance of 80 cm or 1 meter, and a plant distance of 100 cm. Plant the cuttings upright, about 10 cm deep in the soil. Spraying chemicals to control weed seed germination. When planting in the rainy season, the soil is typically moist, and chemicals should be applied within 3 days after planting cassava to control weed germination immediately or before the cassava plants emerge. If sprayed after the cassava plants sprout, the plant may be damaged. These interactions can range from climatic extremes that influence spray coverage and field access to direct effects of CO_2 or temperature on plant biochemistry and morphology [23]. The use of chemical fertilizers (e.g., urea, calcium nitrate, ammonium sulfate, diammonium phosphate, etc.) has great importance for the world's food production, as it works as fast food for plants, causing them to grow more rapidly and efficiently. However, adverse effects are being observed due to the excessive and imbalanced use of these synthetic inputs [24].

The first step involves weeding and fertilizing the plants. The first weed control should occur approximately 30–45 days after planting, using a small walk-behind tractor or a disc cultivator to eliminate weeds. We attached chemical fertilizers to the tractor's back, placing them 20 cm away from the cassava plants. We used a hoe to remove the remaining weeds. Along with covering it with fertilizer, it can be added by digging a hole 20 cm away from the base of the tree and then filling it with soil. Fertilizers should be applied while the soil is still moist. Apply weed control a second time, approximately 60–70 days after planting, using the same method as the initial application. If necessary, remove weeds a third time using a hoe or herbicide spraying. Use a cover on the spray nozzle to prevent chemicals from entering the cassava's buds and stems. However, one of the most significant carbon footprint "hotspots" for intensive agriculture is the use of fertilizers [25]. Cassava can be harvested at an appropriate age, which is approximately 10–12 months, after planning and preparing the cassava cuttings. For the next planting, chop and leave unused cassava plant parts (leaves, branches, and stems) in the plot to use as green manure [26]. Cassava stores the organic carbon it absorbs for photosynthesis in its roots, rhizomes, stems, and leaves. Plowing and covering the rhizomes, stems, leaves, and tubers left after harvest is therefore beneficial for reducing GHG emissions from cassava harvesting [27]. Cassava takes in carbon dioxide; plants open tiny pores in their leaves (called stomata) that allow water to exit through transpiration. They found that when carbon dioxide levels increase from 400 to 600 ppm, cassava leaves can conserve 58 percent more water on average by optimizing stomatal conductance, which is the rate at which carbon dioxide enters compared to water exiting the leaf [28].

One of the problems of agricultural cultivation is its adverse effects on global warming. Therefore, we studied GHG emissions from different methods of fertilizing cassava to help reduce GHG emissions. By assessing the carbon footprint of different fertilization strategies in cassava cultivation, we aim to recommend strategies that help reduce GHG emissions on an international level. This study begins with the acquisition of raw materials and continues until they are processed into a cassava product. The volume of GHGs released in terms of carbon dioxide equivalents (CO_2 equivalent) using the global warming potential value in 100 years (GWP100) is as follows: $CO_2 = 1$, $CH_4 = 28$, and $N_2O = 265$ [29].

2. Materials and Methods

Life cycle assessment (LCA) is a method for analyzing and quantifying the environmental impacts of producing a product or undertaking various activities [30]. This assessment considers the entire life cycle, including the extraction or acquisition of raw materials, the production process, transportation, and the use, maintenance, and distribution of the product. When considering the impact of the production process on the environment, the ecosystem, and hygiene, as well as environmental problems, the quantities of energy and raw materials used must be specified. The calculation must also include the amount of waste released into the environment. The ultimate aim is to improve the product and production processes that have the least environmental impact [31]. Carbon footprint analysis is a key indicator for mitigating environmental impacts. The carbon footprint is based on LCA methodology, which focuses only on the effects of global warming potential. The carbon footprint is defined as the total quantity of inputs within the system boundary used in the process that affects the overall quantity of global warming (output). Currently, to meet ISO 14040 standard requirements, the focus of this relies mainly on four requirements: 1) Definition of goals and scope, 2) Life cycle inventory analysis, 3) Assessment of life cycle impacts, and 4) Life cycle interpretation.

2.1 The study's goal and scope are defined.

In assessing the carbon footprint from cultivating cassava, one must account for the potential GHG emissions, which include estimated amounts of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). We evaluated these according to the model "Cradle to Farm Gate," from the acquisition of raw materials through production practices until the product was sold [32]. Therefore, this study aimed to evaluate the reduction rate of GHG emissions by comparing global warming potential values over 100 years [33] from cassava cultivation using either chemical fertilizers or liquid organic biofertilizers. This study was conducted using 9 experimental plots with 3 replicates and various fertilizer applications (including a control), each plot measuring 1600 m^2 in the northeastern region of Thailand. We followed the guidelines of ISO 14040:2006 and calculated the carbon footprint of the material input, followed by Thailand's IPCC methodology, to assess the impacts (ISO 14040:2006, 2020). Finally, the results of the evaluation served as guidelines for cassava plantation farmers to promote good cultivation practices that minimize environmental impact while maintaining product quality. Data was collected from experimental plots during the 2023 planting season. Also, the harvesting data from the cassava experimental plots were analyzed for variance to find the average value using Tukey's method and family error range, by using the yield data to analyze and compare how effective and different the use of bio-fermented liquid from the fermentation process is compared to the use of chemical fertilizers and no fertilizers (control), with a confidence level of 95%.

2.2 Functional unit.

The study units were the biomass yields of cassava roots from each experimental plot and the quantity of fertilizer applied. These measures were used to calculate the annual quantity of carbon released by the quantity of fertilizer. These measures, which calculated carbon emissions from planting cassava, served as a unit of measure for evaluating the system's performance and were used to compare the relationship between inputs and outputs, making it possible to assess the three different planting methods and estimate GHG emissions [34]. The working units being compared are the same. Therefore, the functional unit used in this study was 1000 kg of harvested cassava, excluding transport and biomass removal after harvesting.

2.3 System boundary.

The system boundary includes cassava cultivation activities and root crop harvesting, excluding transportation to the sub-purchasing yard and removal of cassava residues. However, the system boundary encompassed various approaches to obtaining the product [35], as illustrated in Figure 1.

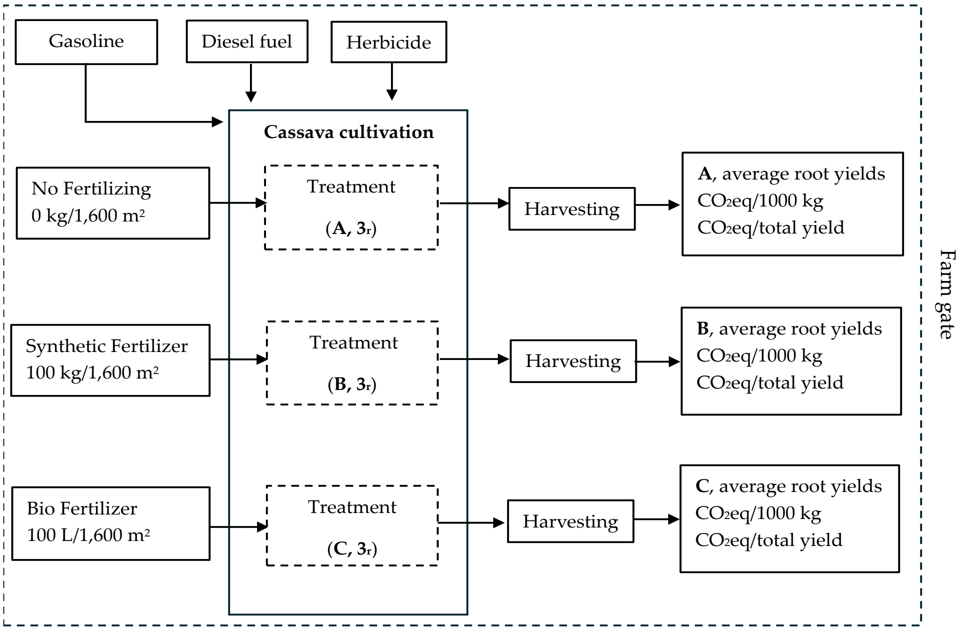

Figure 1. System boundary of cassava cultivation.

The carbon footprint is generally estimated by multiplying activity data by standard emissions factors [35]. Data collection for carbon footprint analysis included primary data obtained from experimental plots. Data collected from the three Cassava experimental plots were used to prepare an environmental life cycle inventory. Secondary data were obtained from database sources in Thailand, including the Life Cycle Database and carbon footprint databases, as well as related research that considered information similar to the situation in Thailand. This information was supplemented by data from international organizations and general publications, such as those by the IPCC. Normally, cassava cultivation relies on the addition of both synthetic and organic fertilizers. The recommendations for using different fertilizer formulas depend on the type of soil. In areas with sandy loam soil, a synthetic fertilizer with a formula of 15-15-15, applied at a rate of 100 kilograms per 1,600 m², is recommended. Such an outcome is generally achieved by adding fertilizer as a foundation, plowing for planting, and fertilizing the plants when they are about 2 months old or more. Non-chemically synthesized biofertilizers are biodegradable and can serve as fertilizers [36]. Biofertilizers are preparations that contain live or latent microorganisms. They are easy to handle, can be stored for a long time, and are also effective as biological fertilizers. Biofertilizer formulas act as carriers for microorganisms, transporting them from the production source to the soil in the plantation. [37] Liquid organic biofertilizer is a sustainable and environmentally friendly agricultural technique. Using organic biofertilizer helps increase crop yields, improve soil fertility, and enhance the nutrient content in the soil. Various organisms can be utilized as organic biofertilizers to increase soil fertility without causing pollution from biodegradation. [38]. Therefore, the production of bioorganic fertilizer for cassava cultivation in experiments was conducted using different amounts of cassava roots and molasses, supplemented with certified organic material and added microorganisms (Actinomyces). Namely Bio-1: 1 kg of fresh crushed cassava root, 1 kg of molasses. Bio-2: 1 kg of fresh crushed cassava, 2 kg of molasses. And-Bio-3: 1 kg of fresh crushed cassava, 3 kg of molasses, as materials for anaerobic bio-fermentation. All bio-fermented water is analyzed using a technique that examines plant nutrients in bio-fermented water to determine primary and secondary nutrients, such as nitrogen, which is digested and distilled, and then titrated with acid to measure the amount of nitrogen (Kjeldahl method). We digest phosphorus with acid, color it, and measure it using a UV-visible spectrophotometer. Calcium, magnesium, and potassium, as well as other cationic elements, can be digested with acid and then measured with an atomic absorption spectrophotometer. A pH and conductivity meter directly measures the pH and conductivity tests [39]. Liquid organic bio-fertilizer from fermentation process results and the values of the Macronutrients obtained from the laboratory analysis, the bio-organic liquid fertilizer contains the macronutrients in the amount that will be used for cultivation: Bio-3, contains 2.23 % of total macronutrients, Bio-2 contains 0.89 % of macronutrients, and Bio-1 contains 0.72 % of macronutrients [40]. Spraying liquid organic biofertilizer both through the roots and through the leaves will begin when the plants have been in place for 2 months or more, similar to the application of chemical fertilizers. In this trial, the cassava cultivation in both experimental plots had sandy loam soil. The soil analysis revealed the following characteristics from 9 experiment plots before planting cassava: most of the soil in all plots was highly acidic, with an average pH of 4.98, and the average potassium content across all plots was 18.83%. As for organic matter (OM) in the soil from the analysis results, all soils are at low levels with an average of 1.2% and the suitable soil for cassava cultivation should be 1.5 - 2.5% (Land Development Department, referring to OM, Walkley and Black). Only phosphorus (P_2O_5) is available in high quantities, especially in the soil of the cassava experiment plot 1, which is as high as 31%. Therefore, an appropriate median phosphorus value for cassava cultivation plots is 11-15% (Land Development Department, referring to Available P, Bray II). pH 4.98, organic matter 1.12%, phosphorus 18.83%, and potassium 29.33% [41].

The synthetic fertilizer usage for the synthetic fertilizer plot (Treatment B) was 46-0-0, 15-15-15, and 0-0-60 at a total quantity of 100 kg per 1600 m² [42]. The liquid organic biofertilizer plot (experimental plot C) received 100 liters of liquid organic fertilizer per 1600 m², while Treatment A applied no fertilizers (Control plot). We applied chemical fertilizer and liquid organic biofertilizer to the soil when cassava had been planted for 2, 3, and 4 months, and harvested the product 12 months later. The cultivation activities of cassava remain consistent, except for the types and amounts of fertilizer applied. (1) Fuel and other petrol use. We used a tractor to plow the soil in the planting plots. We plowed furrows to plant cassava stems and remove fresh cassava roots. Diesel was mainly used. At 1 rai per hour, it has a fuel consumption rate of approximately 1.5–5 liters per rai (T1, T2, T3). Tillage the cassava experimental plots. Cassava cultivation does not involve tillage to reduce soil compaction, as cassava is sensitive to growth in compacted soil with poor water drainage. The procedure restores the physical and chemical properties of the soil to their original state while also enhancing the soil's potential to improve the stability of the soil structure in the plot. Then, cassava can be grown without tillage, allowing the plant to grow optimally and produce the desired yield while maintaining the physical properties of the soil [43].

- Raise the ridges to plant cassava stalks in every experiment plot. Raise the ridges to plant cassava, as the rainy season floods the area. Plow the planting furrows with a height of 30-40 centimeters and a distance between furrows of 100-120 centimeters to drain water and facilitate weeding and harvesting [44]. The planting area is raised to form a ridge, allowing for efficient drainage and preventing water retention. This prevents the cassava roots from absorbing oxygen, which can cause fungal diseases and limit nutrient absorption [45].

(2) And, no fertilization activities were performed in the control plots (TA)

(3) Chemical fertilizer application (TB). Cassava plants were fertilized 2 months after planting, and the soil in the cassava plantation was fertilized three times:

- 1st apply fertilizer formula 46-0-0, 25 kg,
- 2nd apply fertilizer formula 15-15-15, 50 kg,
- 3rd apply fertilizer formula 0-0-60, 25 kg,

(4) The experimental plot (TC) serves as the testing ground. An aerobic fermentation process produces liquid organic fertilizer. The process employs a solid fermentation technique that utilizes cassava roots left in the field after previous harvests as the raw material for fermentation. It is ground and dipped into a stirred fermentation tank, and actinomycete microorganisms are added. Molasses is used as a carbon source, and specific organic materials are utilized as culture media to produce liquid bio-fermented water, which is used in cassava cultivation. The electricity in the fermentation process, both stirring and electrolysis, comes from solar panels. The selected microbial strains are bacteria that are efficient in decomposing agricultural products or waste, and there is also a beneficial Aspergillus fungus. Liquid organic biofertilizer from the three reactor tanks process was collected and sprayed on the soil 3 times after planting cassava in the 2nd, 3rd, and 4th months:

- 1st soil spray with Bio formula .25-.02-.45, 20 L *[06].*
- 2nd soil spray with Bio formula .25-.04-.60, 30 L *[06].*
- 3rd soil spray with Bio formula .20-.83-1.2, 50 L *[06].*

(5) Herbicide is used to control weeds with chemicals. We can classify the chemicals for weed control into two categories based on the duration of their use: 1) use of pre-emergence herb control chemicals, sometimes called control agents or contraceptives, using chemical sprays (500 cc) as soon as cassava planting

is finished or no more than 3 days before weeds and plants germinate, and 2) chemicals to control weeds after emergence (weed killer), using herbicides when the cassava is more than 4 months old (T1, T2, T3) and the stem is more than 70 centimeters tall [46].

(6) Harvesting cassava products. When it's time to harvest fresh tubers for sale to the sub-purchasing yard, the harvesters gather cassava. Agricultural machinery is used to dig up cassava roots, and labor is used to collect cassava production [47].

2.4 Impact of the emission factor.

Emission factor values are associated with emissions. Precise information on EF is crucial for estimating emissions from a given system, as outlined in the guidelines provided by the IPCC report. We express EF by dividing the weight of a specific gas by the unit weight, volume, distance, or duration of the polluting activity. This study is based on a methodology for evaluating emissions and emission factor values, as outlined in guidelines for the carbon footprint of products. The evaluation of life cycle results in this experiment suggests the possibility of global warming over the next 100 years, focusing solely on the quantities of carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O) that will be emitted. We adjusted the global warming potential (GWP) over 100 years in 2021 to align with the country's GHG emissions assessment. The GWPs of CO_2, CH_4, and N_2O are 1, 28, and 265. GHG emissions to the atmosphere as kg CO_2e were calculated according to the following formula: Equation 1

$$CF = \sum(Activity\ data_i\ x\ EF_i) \tag{1}$$

Where:

CF = Carbon footprint (kg CO_2eq)
Activity data = Quantity of input or activity (e.g., kg of fertilizer, liters of fuel)
Emission factor = Emission factor for each input/activity (kg CO_2eq per unit), as shown in Table 3.

Table 3. Thailand National Database emission factor (IPCC).

Items	Unit	EF* (kg CO_2eq/unit)
Urea fertilizer as N (46-0-0)	kg	3.3036
Fertilizer as K2O (0-0-60)	kg	0.4974
Fertilizer as N, P, K (15-15-15)	kg	1.5083
Cassava	kg	0.0489
Molasses	kg	0.1381
Diesel	kg	0.3522
Gasoline	kg	0.4024
Glyphosate	kg	16.0000

Source: (TGO.; Thailand Greenhouse Gas Management Organization) [17]

3. Results and Discussion

3.1 Life cycle inventory of cassava cultivation.

The carbon footprint of cassava cultivation was evaluated across 9 treatment plots (1600 m^2/plot), where the 1st treatment plot served as the control (T1), the 2nd treatment applied synthetic fertilizer (T2), and the 3rd treatment applied liquid organic biofertilizer (T3), with three replicates (n = 3). The evaluation of carbon emissions included soil preparation, planting, fertilizing, weed control, and harvesting. The data were gathered from the experiments, and to assess GHG emissions, only the average inputs from planting and harvesting cassava were considered for the results in each experiment. The collection of environmental inventory data used to evaluate the carbon footprint from cassava cultivation in Chaiyaphum Province, Thailand, was conducted during planting activities using the KU-50 cassava variety in 1,600 m^2 experimental plots. We studied the data obtained from the experimental plots. The control plots yielded an average of 1658 kg/1600 m^2, using chemical fertilizers produced a yield of an average of 3552 kg/1600 m^2, and using biofertilizers produced a yield of an average of 7605 kg/1600 m^2. The list of acquisitions of 1000 kg of cassava was analyzed, and the weight of fresh cassava roots per area was taken from the average weight of each experimental cassava planting plot. In summary, the results showed that the plot using liquid organic biofertilizer (Bio-1, 2, 3) had the best effect on total yield and was significantly different from the other planting methods ($P < 0.05$), as indicated in Table 4.

Table 4. Average cassava root yields per experiment plot.

Treatment	Applied (kg, L/rai)	Root yield R_1, (kg /rai)	Root yield R_2, (kg /rai)	Root yield R_3, (kg /rai)	Average root yield (kg /rai)
Control (T1)	0-0-0	1520	1488	1968	1658.67^c
Che-Fertilizer (T2)	100 kg	4496	3008	3152	3552.00^b
Biofertilizer-1,2,3 (T3)	100 L	8336	6864	7626	7605.33^a
Mean =					4272
P = 0.000					***

Note*** = statistically highly significant difference ($P < 0.000$); Different letters labeled in the same column showed statistically highly significant differences ($P < 0.000$) using Tukey's family error range test.

Cassava will be planted using three methods: a control plot, chemical fertilizers, and organic liquid fertilizers, with each method applied three times. Apply chemical fertilizers and liquid organic biofertilizers to cassava plants 45 days after planting, using chemical fertilizers at a rate of 100 kg per rai and biofertilizers at a rate of 100 Liters per Rai. This approach will evaluate the planting activities until the cassava harvest, including the yield rate, which affects greenhouse gas emissions. Preliminary results: The plot using biofertilizers (T3) produced root yield at a rate of 7.6 tons/rai and increased by 114% compared with the plot using chemical fertilizers (T2) and 358% compared to the control plot (T1).

Carbon Footprint (CF) from cassava cultivation, control, nitrogen fertilizer, and biofertilizer plots.

Calculation of carbon footprints from cultivation to estimate greenhouse gas emissions associated with various activities from cassava cultivation to harvest, considering emissions from land preparation, fertilizer use, herbicides, and energy (machinery) use, to use data for life cycle assessment (LCA) framework, considering emissions from all steps from cultivation to final harvest. The amount of pollutant emissions from plowing the ridges and harvesting in cassava plantation areas is expected to be affected by the use of pollutant factors, including the type of fuel used for land preparation machinery and fuel consumption of 4.5 liters. Emissions related to the production of glyphosate, a weed control chemical, and the burning of weeds that have already sprouted in cassava fields, with an average of 1 liter used. In control plots, gasoline is used in sprayers, with no electricity used, and the average consumption is 5 liters. The calculations indicate that 1000 kg of cassava can produce 11.80 kg CO_2eq, and CF/ton is calculated from (4.5 x 0.3522) + (5 x 0.4024) + (16 x 1) / 1.658 = 11.80, and the carbon footprint of the total yield was 19.60 kg CO_2eq, and CF/yield is calculated from (4.5 x 0.3522) + (5 x 0.4024) + (16 x 1) = 19.60, as shown in Table 5.

Table 5. Life Cycle Inventory (LCI) data of cassava root production with Control plot (T1), (1658 kg/1600 m^2).

Control plot	Quantity (kg/1600 m^2)	Carbon footprint		
		Source (kg CO_2eq)	Use (kg CO_2eq)	Total (kg CO_2eq)
2nd month, no fertilizing	0	0	0	0
3rd month, no fertilizing	0	0	0	0
4th month, no fertilizing	0	0	0	0
Fuel – Diesel (Land prepare & harvest)	4.50	1.58	-	1.58
Gasoline (Spray herbicide)	5.00	2.01	-	2.01
Glyphosate (Weed killer)	1.00	16.00	-	16.00
Total		19.60		19.60
Total (kg CO_2eq/1000 kg)		11.80	-	11.80

In the control plot, the use of glyphosate herbicide in cassava cultivation was evaluated against the yield per ton and total yield, and the results indicated that it affected greenhouse gas (GHG) emissions by 49.24% and 81.63%, respectively, of the average yield and total yield from the plot, as shown in Figure 2.

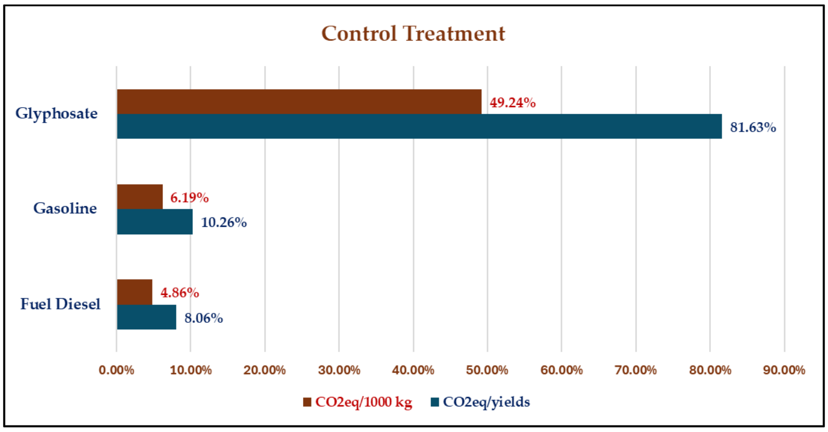

Figure 2. The contribution to the carbon footprint from the weight of 1000 kg and total yields of the unfertilized plot.

The degradation and absorption of chemicals into soil and water can generate nitrous oxide (N_2O), a greenhouse gas that affects the ecosystem and biodiversity.

Chemical fertilizers (TB).

Preparing the land: It is estimated that plowing and harvesting in cassava fields release 4.5 liters of pollutants for every 1,600 m^2, based on the type of fuel used by the machinery and the amount of fuel consumed. Fertilizing: A total of 100 kg of nitrogen fertilizer is used for cultivation, including the formulas 46-0-0, 15-15-15, and 0-0-60. Herbicides: We use glyphosate, a weed control chemical, to burn weeds that have already sprouted in the cassava fields. We use an average of 1 liter per 1600 meters. Sprayers and weed sprays consume an average of 5 liters of gasoline.

A total of 51.83 kg CO_2eq / 1000 kg of cassava weight, and CF/ton is calculated from: (0.46x3.3036) + (55x0) = 1.5196 x 25 = 37.9914 + (0.15x3.3036) + (0.15x1.5716) + (0.15x0.4974) + 0.55x0 = 0.8059 x 50 = 40.29 + (0.60x0.4974) + (40x0) = 0.29844 x 25 = 7.461 + (0.46x25/100) x 44/28 = 0.1807142857 x 265 = 47.8892857105 + (0.15x50/100) x 44/28 = 0.1178571429 x 265 = 31.2321 + (0.3522x4.5 = 1.5849) + (0.4024x5 = 2.012) + (16x1=16) /7.605 = 52.07).

And carbon footprint of total yield was 184.44 kg CO_2eq, which CF/yield is calculated from: (0.46x3.3036) + (55x0) = 1.5196 x 25 = 37.9914 + (0.15x3.3036) + (0.15x1.5716) + (0.15x0.4974) + 0.55x0 = 0.8059 x 50 = 40.29 + (0.60x0.4974) + (40x0) = 0.29844 x 25 = 7.461 + (0.46x25/100) x 44/28 = 0.1807142857 x 265 = 47.8892857105 + (0.15x50/100) x 44/28 = 0.1178571429 x 265 = 31.2321 + (0.3522x4.5 = 1.5849) + (0.4024x5 = 2.012) + (16x1=16) = 184.44), as shown in Table 6.

Table 6. Life Cycle Inventory (LCI) data of cassava root production using synthetic N, P, and K fertilizer (T2), (3552 kg/1600 m^2).

Chemical fertilizer (N, P, K)	**Quantity (Kg, L/1600 m^2, T2$_{r1,2,3}$)**	**Carbon footprint**		
		Source (kg CO_2eq)	**Use (kg CO_2eq)**	**Total (kg CO_2eq)**
2nd month, apply 46-0-0	25	37.99	47.88	85.87
3rd month, apply 15-15-15	50	40.29	31.23	71.52
4th month, apply 0-0-60	25	7.461	-	7.46
Fuel – Diesel & 35 hp, tractor usage (hr.)	4.5	1.58	-	1.58
Gasoline	5.0	2.01	-	2.01
Glyphosate	1.0	16.0	-	16.00
Total		105	79	184.4
Total (kg CO_2 eq/1000 kg)		29.60	22.23	51.83

Note: All three chemical fertilizer formulas are used in different quantities.

The carbon footprint of 1000 kg of cassava roots produced using chemical fertilizers is approximately 51.83 kg CO$_2$eq/1000 kg of cassava yield, which relates to chemical fertilizer application and was as high as 25.17 percent, on average, as shown in Figure 3.

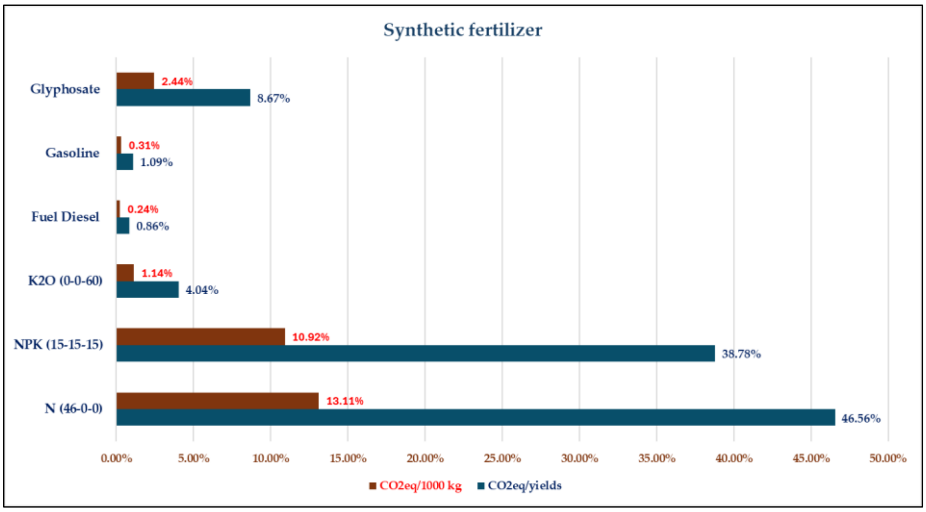

Figure 3. The contribution to the carbon footprint from the weight of 1000 kg and the total yields of cassava roots when using chemical fertilizers.

The use of chemical fertilizers in cassava production is a significant contributor to the overall carbon footprint of cassava cultivation, particularly in the production and application of synthetic fertilizers. Nitrogen fertilizers are a significant source of greenhouse gas emissions, accounting for 85.34% of the total emissions from cassava yield, which was 184.44 kg CO$_2$eq.

Liquid organic biofertilizer was applied to the plots.

Land preparation: The 35 HP tractor is used to plow the ridges and harvest in cassava plantation areas to estimate the effect of using pollutant factors of fuel used for land preparation machinery and fuel consumption of 4.5 liters per 1600 m^2. Biofertilizer application: Using liquid organic biofertilizers with low plant nutrient content will result in a lower carbon footprint compared to synthetic fertilizers, potentially significantly reducing greenhouse gas emissions. The production of organic biofertilizers can help reduce greenhouse gas emissions. The biofertilizers used in cassava cultivation are produced using a developed fermentation process that lowers the cost of compost material and reduces energy consumption during biofertilizer production. Apply 100 liters per 1600 m^2 experiment plot. Moreover, the raw materials used to make biofertilizers are as follows:

Bio-1 uses 1kg of cassava + 1kg of molasses.

Bio-2 uses 1kg of cassava + 2kg of molasses.

Bio-3 uses 1kg of cassava + 3kg of molasses.

Herbicides, such as glyphosate, a weed control chemical, are used, and weeds that have already sprouted in cassava fields are burned, typically using an average of 1 liter.Energy use: Gasoline emissions for use in sprayers in the control plot and no electricity use, averaging 5 liters. A total of 2.74 kg CO$_2$eq / 1000 kg of cassava weight, and CF/ton is calculated from: (0.0489x9) + (0.1381x6) + (0.3522x5) + (0.4024x4.5) + (16x1)/7.605 = 2.80. The carbon footprint of the total yield was calculated to be kg CO2eq, as well as CF/yield, which is calculated from: (0.0489 × 9) + (0.1381 × 6) + (0.3522 × 6.5) + (2.02 × 5) + (16 × 1) = 20.85, as shown in Table 7.

Table 7. Life Cycle Inventory (LCI) data of cassava root production in liquid organic biofertilizer applications (T3) (7605 kg/1600 m^2).

Biofertilizer (N, P, K)	**Quantity (L/1600 m^2)**	**Carbon footprint**		
		Source (kg CO_2eq)	**Use (kg CO_2eq)**	**Total (kg CO_2eq)**
2nd month, spray bio-1, 0.25-0.02-0.45	20	0.28	-	0.28
3rd month, spray bio-2, 0.25-0.04-0.60	30	0.42	-	0.42
4th month, spray bio-3, 0.20-0.83-1.20	50	0.56	-	0.56
Fuel Diesel (soil preparation & harvest)	4.5	1.58	-	1.58
Gasoline (spraying herbicide)	5.0	2.01	-	2.01
Glyphosate (weed control)	1.0	16.0	-	16.0
Total		20.85	-	20.85
Total (kg CO_2eq/1000 kg)		2.74	-	2.74

Note: All three formulas of liquid organic biofertilizer are made from cassava roots and molasses fermented in different quantities.

The carbon footprint of cassava grown in a sandy loam soil plantation, using liquid organic biofertilizer and sprays, yielded approximately 2.74 kg CO_2eq (0.79%/ton) for every 1000 kg produced per 1600 m^2, which is lower than that of other planting materials used in the plot, as shown in Figure 4.

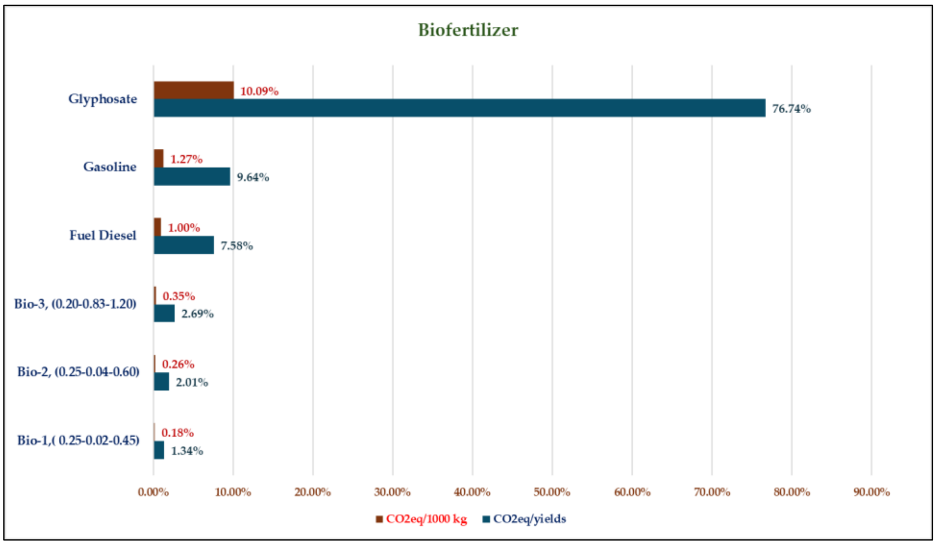

Figure 4. The contribution to the carbon footprint from the weight of 1000 kg of cassava roots when using liquid biofertilizers.

Using liquid organic biofertilizers in cassava cultivation can help reduce carbon emissions when compared to the total weight of cassava roots per area. The greenhouse gas emissions from liquid organic biofertilizers per 1,600 m^2 of cassava production are 20.85 kg CO_2eq (6.04%). The emissions are related to production, which is the main factor affecting the overall carbon stock of cassava cultivation.

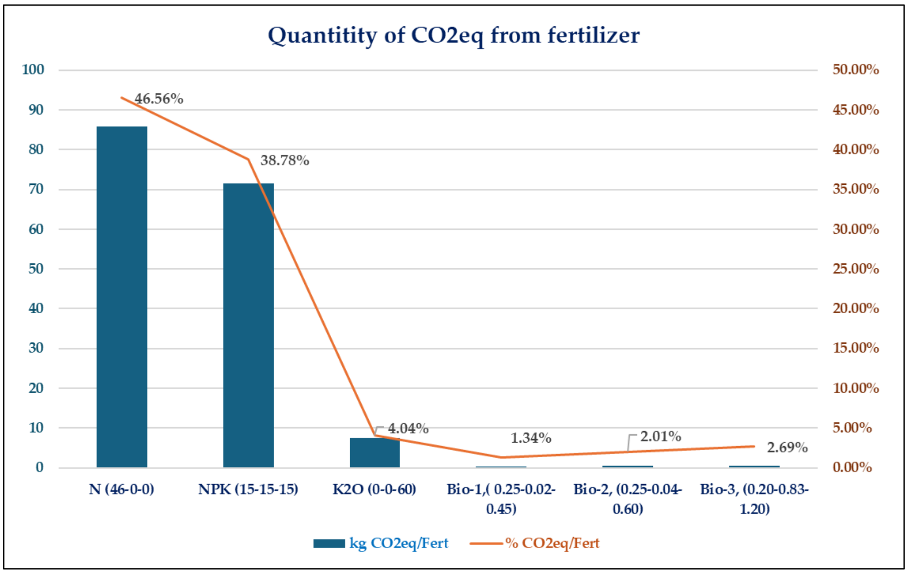

Figure 5. Total contribution of carbon footprint fertilizers.

3.2 Life cycle inventory results and discussion.

The carbon footprint of cassava cultivation from "cradle to farm-gate" for the TA, TB, and TC methods, as well as the carbon footprint associated with cassava root yield, was 11.80 kg CO_2eq/1000 kg, 51.83 kg CO_2eq /1000 kg, and 2.80 kg CO_2eq/1000 kg, respectively; this was observed in an experimental design that varied fertilizer types and amounts. The carbon footprint in cassava cultivation is primarily attributed to the use of chemical fertilizers, which release N_2O gas during their production and application. Cassava cultivation using chemical fertilizers (TB) still significantly impacts approximately 89% of the carbon footprint on cassava yield. On the other hand, the yield of TB cassava was only 50% higher than that of TA and 50% lower than that of TC. At the same time, the cultivation cost was higher than that of all other cultivation methods, and the impact of greenhouse gas emissions was greater than that of other plantations. The carbon footprint of cassava cultivation treatment A (control) with no fertilizing and harvesting of yields, evaluated in kg CO_2eq per 1000 kg, was 11.80. B, including cultivation and harvesting of yields, was evaluated in kg CO_2eq per 1000 kg and was 51.83. The carbon footprint of cassava cultivation treatment C, including cultivation and yield harvesting, was 2.80 kg CO_2eq/1000 kg of root product. The impact of global warming potential varied depending on the type of fertilizer used, and a significant increase in yield was observed. This means that using chemical fertilizers in cassava cultivation will increase the quantity of GHG emissions every year. The use of liquid organic biofertilizers is considered to have minimal GHG emissions. A more carbon-neutral strategy would be to switch from synthetic to liquid organic biofertilization of cassava crops. Furthermore, yields were increased when using liquid organic fertilizers, demonstrating the advantages of this type of fertilizer, which has a significantly reduced environmental impact. This study was conducted over a single growing season in a specific region of northeastern Thailand, which may limit the generalizability of the findings to other regions or agricultural conditions. We did not thoroughly analyze the economic feasibility and supply chain constraints of liquid organic biofertilizers, particularly in terms of production costs, scalability, and farmer accessibility. These limitations suggest that, while promising in terms of environmental benefits, broader adoption would require further study across multiple seasons, agro-climatic zones, and economic contexts. However, we must adopt a sustainable approach to reduce production costs without compromising the environment.

Liquid organic bio-fertilizers can vary significantly in nutrient concentrations and are pricier than chemical fertilizers. Large-scale and prolonged use can accumulate salts, nutrients, and heavy metals, which can have adverse effects on plant growth, soil organism development, water quality, and human health. Large-scale use of organic bio-fertilizers is necessary for the soil because they contain fewer nutrients than chemical fertilizers. Primary nutrients may not be sufficient for plant growth and development, and nutrient deficiencies may occur, which are caused by low transfer of primary and secondary nutrients. To overcome the limitations of liquid organic biofertilizer production, low-cost techniques should be employed. For instance, liquid organic biofertilizer can be made from inexpensive cassava roots and supplemented with organic nutrients, such as those obtained through aerobic fermentation processes, which can help reduce CH_4 emissions. Collecting the remaining cassava roots in the field after harvest, instead of letting them decompose naturally (anaerobically), crushing them, and fermenting them in an aerobic reactor tank to produce an organic liquid biofertilizer, can reduce CH_4 emission during decomposition. Clean energy sources, such as solar panels, operating at low DC voltage, should be considered to create a redox balance reaction by producing reduced carbon compounds (fermentation) and reducing electricity use in biofertilizers.

4. Conclusions

From a study of the carbon footprint of cassava, calculated per 1000 kg of cassava yield, the scope of the study encompasses the entire process, from acquiring raw materials through cultivation and harvesting to the production of the final product. This study was conducted in nine planting plots, each of 1600 m^2, in the Khon Sawan District, Chaiyaphum Province. This study found that planting cassava using chemical fertilizers resulted in an average cassava yield of approximately 3,552 kg per 1,600 m^2. The carbon footprint analysis results for fresh cassava were estimated to be approximately equal to 51.83 kg CO_2eq/1,000 kg and 184.4 kg CO_2eq/1,600 m^2 of planting area. Meanwhile, the treatment using organic liquid biofertilizers yielded an average cassava yield of approximately 7,605 kg/1,600 m^2. The carbon footprint analysis results for fresh cassava were estimated to be approximately equal to 2.74 kg CO_2eq/1,000 kg. The total per area was 20.85 kg CO_2eq/1600 m^2. Considering the carbon footprint from Thailand's average cassava planting area of 13,064,186,880 m^2 in 2018–2022, chemical fertilizer applications would result in GHG emissions equivalent to 1,505,647,537 kg CO_2eq/year. Using liquid organic biofertilizer would result in a much lower GHG emissions rate of 170,242,685 kg CO_2eq/year. Therefore, experimental plots with cultivation methods using chemical fertilizers have the highest GHG emissions over the entire life cycle. Meanwhile, liquid organic biofertilizers and fertilizers have the lowest GHG emissions. Therefore, liquid organic biofertilizers that use agricultural waste materials would significantly reduce cassava's carbon footprint. In addition, the yield of cassava using liquid organic biofertilizers alone has been shown to increase by over 2 times that when using chemical fertilizers alone. Hence, liquid organic biofertilizers from agricultural products have high economic and environmental value, reduce the cost of agricultural crop production, are less harmful to people than inorganic fertilizers, reduce pollution, and improve soil fertility without the accumulation of heavy metals and long-term residues from biodegradation, resulting in higher yields while having less impact on the environment. However, nationwide implementation would face challenges related to scalability, cost-effectiveness, farmer acceptance, and the development of the supply chain. These factors must be addressed to realize the full potential of GHG reduction at the national level.

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