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Biological treatment of solid sludge from palm oil extraction for organic farming at the dawn of climate change

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ABSTRACT

Cameroon, one of Africa's leading palm oil-producing countries, is currently increasing its production rate due to growing global demand. However, this growth raises environmental concerns due to the production of enormous amounts of waste during the extraction process, including solid sludge that generates CO2 emissions responsible for global warming and climate change. Reducing the environmental impact of palm oil agro-industries through better waste management practices is essential not only for sustainable palm oil production but also for agricultural purposes. The method used in the waste management system is biostimulation coupled with bio-increase of the indigenous microorganisms. Composting parameters such as temperature, pH, electrical conductivity, water content, organic carbon content, and C/N ratio were monitored to ensure proper composting and compost maturity. Minerals of agronomic interest, such as N, P, K, and Mg, were analyzed to verify the quality of the resulting compost. The evolution of the composting parameters in all treatments showed optimal trends for the metabolic activity of microorganisms, thus allowing good degradation of organic matter. All treatments resulted in a mature final compost after 60 days, containing a considerable amount of nutrients and meeting compost quality standards. The different composts resulting from the treatment of palm oil solid sludge can therefore be used as a soil amendment to reduce the importation and use of chemical fertilizers.

Contribution/Originality: The results of this study contribute to the advancement of knowledge on the degradation process and sustainable management of solid palm oil sludge that comes directly from the factory of the Cameroonian palm grove company (SOCAPALM-Mbambou). The degradation of this solid sludge makes it possible to depollute the environment and use it as a fertilizer in order to promote organic farming.

1. INTRODUCTION

The oil palm (*Elaeis guineensis*) is a perennial monocotyledonous plant of the Arecaceae family, native to West Africa, and is primarily cultivated for its palm oil, which is extracted from the pericarp of the fruit [1]. Palm oil plays a key role in meeting global food needs and contributes significantly to the economic development of producing countries. In Cameroon, a production of 465,000 t was recorded during the 2021-2022 harvest season, placing it third in Africa and twelfth in the world behind Nigeria (1,400,000 t) and Ivory Coast (600,000 t) [2]. The increasing uses of palm oil (cosmetics, energy, biofuels, agri-food, etc.) have increased its demand. Currently, global demand exceeds supply, and this trend is likely to intensify in the future, making it a particularly attractive product for investors.

According to OECD and FAO forecasts, global palm oil production is expected to grow by 20% between 2021 and 2030. Supply, therefore, remains significantly below the strong demand [3].

Due to this ever-increasing demand, many investors have sought land to expand oil palm plantations and improve production. This has led to the opening of land where virgin forests are cleared for plantations. According to Food and Agriculture Organization [4] twenty-one million hectares of forest worldwide and 170,169 hectares in Cameroon have been destroyed for oil palm plantations. As a result, the expansion of oil palm plantations is causing not only biodiversity loss but also increased environmental pollution [5]. To ensure the sustainability of oil palm production, several implementation guidelines were proposed by the Roundtable on Sustainable Palm Oil (RSPO) in August 2003, including biodiversity conservation, land management, soil and water conservation, no-burn replanting, waste treatment, and recycling of industry by-products.

Although the oil palm industry is recognized for its contribution to economic growth and rapid development in Cameroon, it also contributes to environmental pollution due to the production of large amounts of waste during the extraction process. More than 70% (by weight) of the fresh fruit bunch remains as palm oil waste during the extraction process [6]. These wastes are mainly liquid discharges, stalks, solid sludge from three-phase centrifugation, fibers, and shells. The management of these wastes poses significant challenges for palm oil agro-industries. Some of these wastes, such as fibers and shells, are regularly used for energy production in boilers. The method of managing empty fruit bunches and solid sludge practiced by palm oil agro-industries in Cameroon is to dump them in the field for natural composting. However, this practice causes environmental pollution and damages the surrounding environment because this waste takes several years to degrade naturally when dumped in the field. During this time, it clogs and waterlogs the soil, thus inhibiting its fertility. When palm oil sludge comes into contact with plants, it inhibits their growth and causes their death [6]. In addition, the leaching of sludge by rainwater causes water depletion and leads to aquatic pollution. Furthermore, solid sludge is responsible for unpleasant odors and therefore a source of disease. Given the abundance of this sludge generated by palm oil milling agro-industries in Cameroon and its impact on environmental pollution, there is an urgent need to implement an effective management system for its treatment, in order to preserve the environment. With this in mind, biological treatment by composting can be a good option for the sustainable management of this waste. Composting would allow the treatment of this waste rich in organic matter and provide the opportunity to use it in the field as organic fertilizer. This would significantly reduce the use of chemical fertilizers and their impact on the environment. Despite the benefits it could generate, the composting of solid sludge remains to this day an almost non-existent practice in palm oil milling agro-industries in Cameroon.

Several researchers have shown that composting can be a suitable method for converting industrial organic waste into compost that can be used as fertilizer for planting purposes. In addition, the use of compost notably reduces the need for synthetic fertilizers, which decreases environmental contamination and improves soil productivity [7, 8]. Composting has promising potential to mitigate the effects of climate change. It could significantly reduce methane emissions from sewage systems, making it a valuable tool in the fight against global warming [9]. Composting organic waste significantly reduces the amount of waste disposed of in landfills or oceans, thus reducing the emission of harmful substances and mitigating their negative impacts on marine life, air quality, and the environment as a whole [10]. Composting not only has environmental benefits but also improves soil quality and structure, increasing its water-holding capacity, promoting aeration, and facilitating the growth of beneficial microbes [11]. In addition, the introduction of compost into agricultural land increases soil fertility by enhancing the availability of plant nutrients and organic matter [12] some techniques have been introduced to improve the composting process, increasing the degradation rate and the quality of the final compost, including the addition of readily biodegradable waste or microorganisms [13, 14]. The objective of this work is to contribute to the reduction of environmental pollution from palm oil agro-industries through improved waste management practices for sustainable production.

2. MATERIALS AND METHODS

2.1. Materials

The palm oil sludge and oil palm stalk samples used in this study were collected at the Cameroonian palm grove company (SOCAPALM-Mbambou), located in Dizangue, Cameroon, in the Littoral region, Sanaga Maritime division, Dizangue sub-division. Sawdust was collected from a sawmill in the city of Douala. Cattle stomach waste was obtained from the Bonendale slaughterhouse, situated in Douala-Bonabéri, Douala 4th sub-division. The various organic materials were transported to the Faculty of Science at the University of Douala, located in Douala 5th sub-division. The microbial material consisted of a consortium of four bacterial strains isolated from piles of palm oil extraction sludge dumped for more than five months at the SOCAPALM landfill.

2.2. Methods

2.2.1. Experimental Design

The experiment was conducted during the months of July, August, and September 2023, with an average air temperature ranging from 23 to 27°C and an air humidity of 74 to 92%. The experiment was conducted indoors on a concrete floor using a completely randomized block design. The experimental design included four treatments: sludge treated with the stalk substrate with added bacteria, sludge treated with the stalk substrate without added bacteria, sludge treated with the sawdust substrate with added bacteria, and sludge treated with the sawdust substrate without added bacteria, each replicated twice. These treatments are designated as T1, T2, T3, and T4, respectively. The 8 experimental compost windrows followed a two-block design, with each block comprising 4 windrows of different substrate types. The spacing between two windrows within the same block was 1.5 m, and the spacing between blocks was also 1.5 m. Each windrow measured 2 m in length, 0.8 m in width, and 0.3 m in height. The factors studied in these trials were the type of substrate and the presence or absence of bacteria.

2.2.2. Composting of Solid Sludge

The method used for solid sludge treatment was bio-increase [15] coupled with slightly modified biostimulation [16]. Eight 250-kg piles of solid sludge were formed, and 10 kg of bovine stomach waste was added to each pile. Four piles received 20 kg of shredded oil palm stalks as a substrate, and four other piles received 20 kg of fine sawdust as a substrate. After adding the various components, the piles were thoroughly mixed with the addition of 50 L of water using a shovel and trampling. The mixed piles were spread to form composting windrows. Subsequently, they were inoculated with 0.5 L of a solution of a mixture of four indigenous bacteria (*Pseudomonas* sp, *Bacillus* sp, *Proteus mirabilis*, and *Klebsiella pneumoniae*) calibrated to an OD = 0.53, isolated from solid sludge from palm oil extraction and having shown a good capacity to degrade palm oil sludge as well as solid sludge from its extraction. To maintain a good moisture level in the windrows, they were watered with water every 3 days until the 48th day. The windrows were turned using a shovel every 3 days until the 48th day to allow sufficient aeration and mixing of the compost constituents. The composting period was 60 days.

2.2.3. Sampling and Physicochemical Analysis of Samples

Compost samples were collected on days 3, 30, and 60 of composting. Composite sampling was performed to obtain a sample that reflected the physical and chemical characteristics of the resulting compost [17]. Approximately 1 kg of in-process compost was collected at various depths (surface, 20, and 40 cm) and at different points within each windrow, then combined into a single composite sample. The samples were divided into two parts: one part was stored at 4°C for physicochemical analyses, and the other was stored at -20°C until the analyses were completed. All analyses were performed in triplicate. Changes in windrow texture and color during composting were assessed through physical observation. Windrow odors were evaluated by sensory perception.

2.2.3.1. Temperature

The temperature of the compost windrows was measured in the upper, middle, and lower layers on day 0, day 3, and every 9 days until the end of composting, using an indoor/outdoor thermometer with a hydrometer clock.

2.2.3.2. Moisture Content

The moisture content was determined on day 0, day 3, and every 9 days until the end of composting by drying 100 g of the sample in an oven at 100°C until a constant mass was obtained. The dried sample was reweighed, and the moisture content was calculated using the formula:

M = [(Ww-Dw)/Dw] * 100 (M: moisture content; Ww: wet weight; Dw: dry weight)

2.2.3.3. Hydrogen Potential (pH)

The pH of the sample was measured on day 0, day 3, and every 9 days until the end of composting using a SARTORIUS AGCOTTINGEN pH meter. The pH was determined according to AFNOR X 31-103. A suspension of solid sludge was prepared in distilled water at a ratio of 5/50 (mass/volume ratio). After stirring for one hour and then settling, the probe was immersed in the solution, and the value was recorded.

2.2.3.4. Exchangeable Bases and Electrical Conductivity (EC)

The method used to extract the exchangeable bases (Mg++ and K+) and determine the EC at pH 7 was that of Pelloux et al. [18]. It was broken down into three stages. First, the bases (Mg^{++} and K^+) were extracted with ammonium acetate (CH_3COONH_4) at pH 7 thanks to the NH_4^+ ions, which saturate the complex and release the basic cations (Mg^{++} and K^+), which were measured by complexometry with EDTA (Ethylene Diamine Tetra-Acetic Acid), for the case of magnesium, while potassium was measured by flame spectrophotometry. Subsequently, the soil was washed with alcohol (95% Ethanol) to eliminate the saturating NH_4^+ solution filling the pores. Finally, the NH_4^+ solution obtained after washing with alcohol was treated with 1 M KCl. Then, the ammonium was determined by Kjeldahl distillation and titration with sulfuric acid (0.01N H_2SO_4) for the determination of EC.

2.2.3.5. Total Nitrogen

Total nitrogen was determined using the Kjeldahl [19] two grams of the sample were mineralized using hot sulfuric acid in the presence of a catalyst (100 g of K2SO4 + 10 g CuSO4 + 1 g selenium) for 3 hours. The mineralized product was filtered, and a fraction was distilled. The ammonia displaced by sodium hydroxide was collected in a sulfuric acid solution (0.01 N) containing a colored indicator (methyl red + bromocresol green, dissolved in ethanol). Nitrogen was obtained after back-titration of the excess sulfuric acid with sodium hydroxide.

2.2.3.6. Phosphorus

Phosphorus was determined using the Bray and Kurtz [20]. This method combines phosphorus extraction in an acidic medium (0.1 N HCl) with complexation by ammonium fluoride (0.03 N NH4F) and aluminum bound to phosphorus. The extracted phosphorus was then determined by spectrophotometry with molybdenum blue using a molecular absorption spectrophotometer or a branded colorimeter (searchteech) at a wavelength of 665 nm.

2.2.3.7. Organic Carbon

Organic carbon was determined using the method of Walkley and Black [21]. This method is based on the oxidation of organic carbon by potassium dichromate (K2Cr2O7) in an acidic medium (H2SO4). The titration of the excess potassium dichromate with ferrous sulfate (FeSO4.7H2O) allows the calculation of the amount of dichromate neutralized by the organic carbon (CO). Organic carbon was obtained by considering that 1 mL of dichromate oxidizes 0.39 mg of carbon. Organic matter was obtained by multiplying the total carbon result by 1.724.

2.2.4. Statistical Analyses

The data were entered into an Excel spreadsheet (Microsoft Office, USA), and graphs illustrating the mean values of the physicochemical composting parameters were generated using Microsoft Excel software. The data were presented as mean ± standard deviation (SD) in graphs and tables. Statistical analyses were conducted using R software version 4.3.3 to perform a one-way analysis of variance (ANOVA). Duncan's test was used to compare differences between treatment means at a significance level of $p<0.05$.

3. RESULTS

3.1. Effectiveness of Solid Sludge Composting

The solid sludge obtained from palm oil extraction was successfully composted using oil palm stalks and sawdust as substrates, whether or not bacterial inoculation was present. Observation of the windrows during the first two weeks revealed that all treatments emitted foul odors, which gradually diminished until day 40 of the composting process, replaced by the humus odor. Thus, the end of the composting process was characterized by the complete disappearance of foul odors and the appearance of an earthy odor, resulting in the transformation of solid sludge from a pasty texture with a brown color to a powdery texture with a color ranging from dark brown to black.

3.2. Study of Composting Parameters

3.2.1. Evolution of Windrow Temperature During Treatment

The evolution of temperature during composting shows a significant effect of day and treatment ($p<0.05$), with the exception of treatments T2 and T4, which do not show a significant difference between days 39 and 48. The temperature evolution curves during the composting process (Figure 1) show that all treatments start from an average temperature of 27.69°C. During composting, three phases of temperature evolution were observed for all four treatments. A thermophilic phase between days 0 and 12, which results in a rapid increase in temperature to 56°C between days 0 and 3, followed by a slight decrease between days 3 and 12, to 40°C. A mesophilic phase between day 12 and day 30, which results in a drop in temperature between 40 and 32°C. A maturation phase between day 30 and day 60, during which the temperature varies very little between 31 and 30°C. The treatments with the addition of T3 and T1 bacteria presented, respectively, the highest temperatures during the composting process (56.03°C and 53.77°C) compared to the treatments without the addition of T2 and T4 bacteria. Furthermore, the treatments with the sawdust substrate presented the highest temperatures during composting compared to the treatments with the stalk substrate.

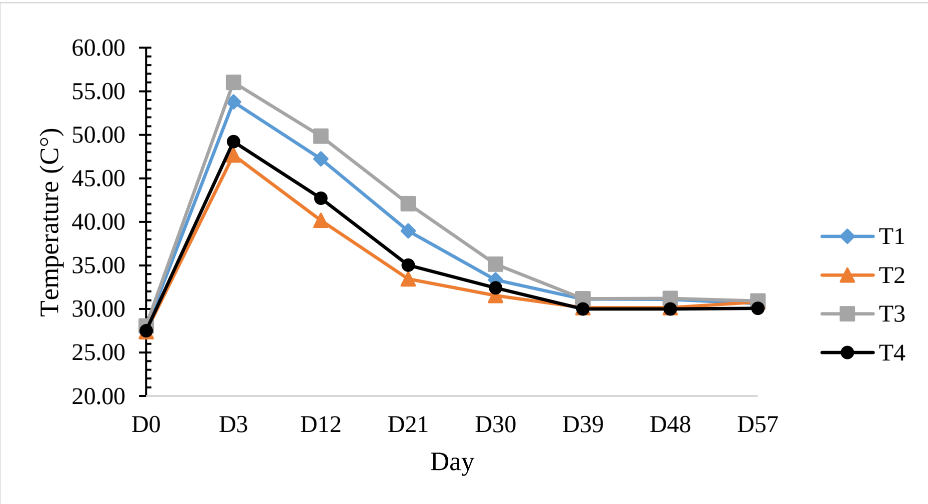

Figure 1. Temperature kinetics during the composting process.

3.2.2. Changes in moisture content of the stalks during treatment

The changes in moisture content during composting show a significant effect of day and treatment ($p<0.05$), except between treatments T3 and T4; T1 and T4 do not show significant differences on day 3 and day 21, respectively. The curves showing changes in moisture content during the composting process (Figure 2) show that all treatments start with an average moisture content of 78%. During composting, a gradual decrease in moisture content was observed across all treatments over time, with a more significant decrease between day 3 and day 30. The composting process resulted in the evaporation of approximately 72% of the water contained in the waste at the beginning of composting. Treatments with sawdust substrate (T3 and T4) exhibited slightly lower humidity levels compared to treatments with stalk substrate (T1 and T2). Additionally, treatments with bacterial inoculum (T1 and T3) demonstrated the lowest humidity levels compared to treatments without bacterial inoculum (T2 and T4).

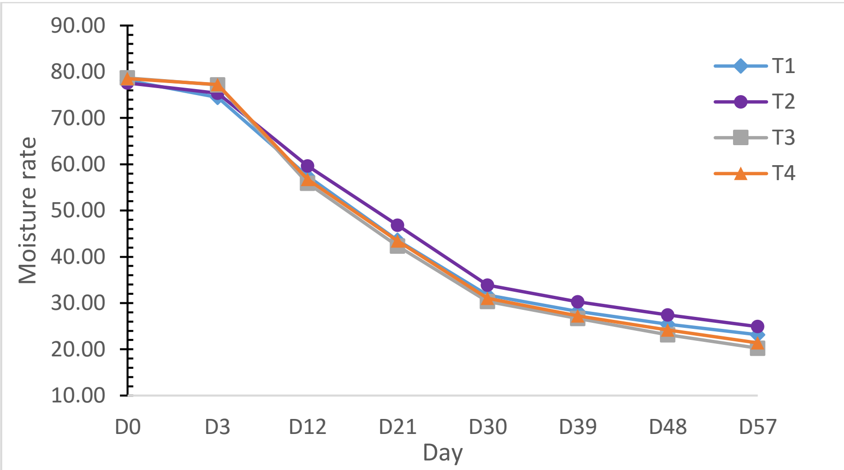

Figure 2. Evolution of moisture content of windrows during the composting process.

3.2.3. Evolution of Windrow pH During Treatment

The results of the analysis of windrow pH during composting show a significant effect of day and treatment ($p<0.05$). According to the pH evolution curve (Figure 3), all treatments initially have a weakly acidic pH, with values of 5.8, 5.8, 6.37, and 6.20 for treatments T1, T2, T3, and T4, respectively. From the third day of composting, a gradual increase in pH is observed in all treatments until day 30, which shows the highest values (between 8.37 and 8.77), thus moving from acidic pH to basic pH. After day 30, a gradual decrease in pH is observed, tending towards neutrality at the end of the composting process in all treatments. Treatments with sawdust substrate (T3 and T4) had the highest pH values compared to treatments with stalks as substrate (T1 and T2). However, treatments with bacterial inoculum (T1 and T3) had the highest pH values compared to treatments without bacterial inoculum (T2 and T4).

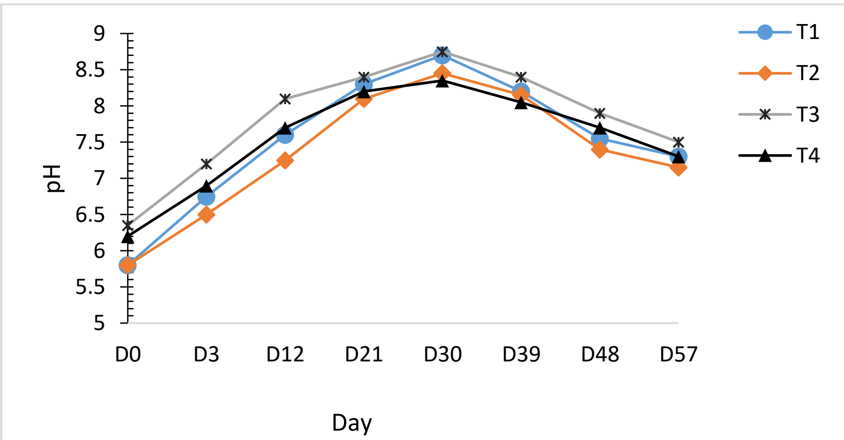

Figure 3. Evolution of pH of windrows during the composting process.

3.2.4. Changes in the electrical conductivity of windrows during treatment

The results of the electrical conductivity analysis in the windrows during composting show that there is a significant effect of day and treatment ($p<0.05$) on the change in electrical conductivity. According to the electrical conductivity curve (Figure 4), all treatments initially exhibited a relatively high value of 5.07 mS/cm. The conductivity trend indicates a progressive decrease across all treatments during the composting process compared to day 0. After day 30, electrical conductivity continued to decline until the end of composting, reaching values of 3.44, 2.99, 2.86, and 2.13 mS/cm for treatments T1, T2, T3, and T4, respectively. Regarding substrate type, treatments with sawdust (T3 and T4) showed lower electrical conductivity values compared to treatments with stalks (T1 and T2). However, the decrease was more significant in treatments with bacterial addition (T1 and T3) than in those without bacterial addition.

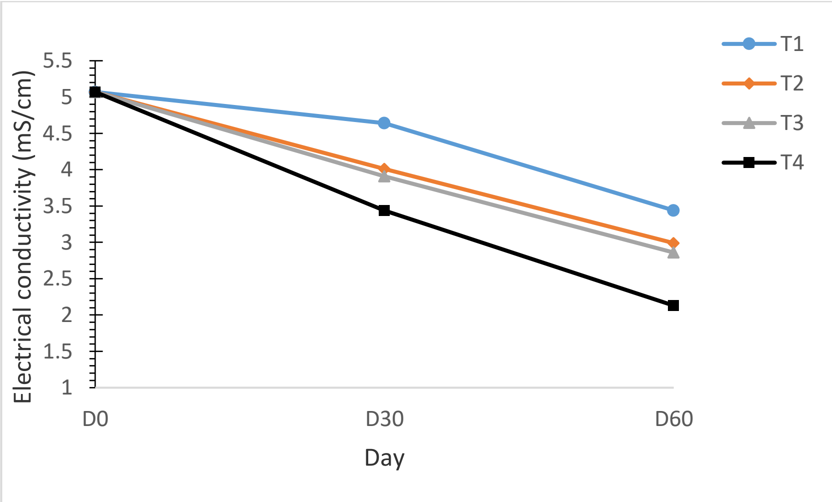

Figure 4. Evolution of electrical conductivity during the composting process.

3.3. Study of Minerals of Agronomic Interest

The evolution of macroelement content (N, P, K, and Mg) during the composting process was presented by treatment (Table 1). A significant difference ($p<0.05$) was observed in the content of the different macroelements between the different treatments on day 0, day 30, and day 60 of composting, except for nitrogen content, which did not show a significant difference between day 30 and day 60 in the treatment with the bacteria-free cob substrate (T2). An increase in nitrogen, phosphorus, and magnesium content was observed in all treatments at day 30 and day 60 compared to day 0. Treatments with the cob substrate plus bacteria (T1) presented increase rates of 128.44%, 74.34%, and 25.29%, respectively, for nitrogen, phosphorus, and magnesium at day 30, and 176.72%, 83.76%, and 41.18%, respectively, at day 60. On the other hand, treatments with the cob substrate without bacteria (T2) presented increased rates of 99.13%, 80.62%, and 19.52%, respectively, for nitrogen, phosphorus, and magnesium at day 30, and 147.41%, 81.67%, and 35.86%, respectively, at day 60. Treatments with sawdust plus bacteria substrate (T3) showed increased rates of 165.51%, 94.06%, and 31.90%, respectively, for nitrogen, phosphorus, and magnesium on day 30, and 201.72%, 109.94%, and 46.23%, respectively, on day 60. Additionally, the increase rates were 109.48%, 78.88%, and 16.47%, respectively, for nitrogen, phosphorus, and magnesium on day 30, and 147.98%, 96.85%, and 32.16%, respectively, for nitrogen, phosphorus, and magnesium on day 60 for treatments with sawdust substrate without bacteria (T4). On the other hand, potassium content decreased significantly ($p<0.05$) from the first weeks of composting in all treatments; the values reached 0.84%, 0.73%, 0.69%, and 0.70% respectively, for treatments T1, T2, T3, and T4 by day 30. After day 30, potassium content continued to decrease in all treatments, reaching 0.78%, 0.53%, 0.47%, and 0.244% respectively, for treatments T1, T2, T3, and T4 on day 60. Overall, treatments with oil palm stalks have slightly higher macroelement contents compared to treatments with sawdust.

Table 1. Evolution of macroelement content during the composting process.

Treatment	Day	Total N (%)	P (%)	K (%)	Mg (%)
T1	D0	1.16±0.04 [a]	0.19±0 [a]	0.88±0 [i]	0.51±0 [a]
	D30	2.65±0.25 [c]	0.23±0 [c]	0.84±0 [h]	0.64±0 [d]
	D60	3.21±0.06 [e]	0.25±0 [f]	0.78±0 [g]	0.73±0 [h]
T2	D0	1.16±0.04 [a]	0.19±0 [a]	0.88±0 [i]	0.51±0 [a]
	D30	2.31±0.05 [b]	0.22±0.02 [b]	0.73±0 [f]	0.62±0.01 [c]
	D60	2.37±0.16 [b]	0.25±0 [e]	0.53±0 [c]	0.70±0 [g]
T3	D0	1.16±0.04 [a]	0.19±0 [a]	0.88±0 [i]	0.51±0 [a]
	D30	3.08±0.10 [de]	0.26±0.01 [g]	0.69±0 [d]	0.68±0 [e]
	D60	3.50±0.02 [f]	0.30±0 [i]	0.47±0 [b]	0.75±0.01 [i]
T4	D0	1.16±0.04 [a]	0.19±0 [a]	0.88±0 [i]	0.51±0 [a]
	D30	2.43±0.11 [b]	0.24±0 [d]	0.70±0 [e]	0.60±0 [b]
	D60	2.88±0.01 [d]	0.28±0 [h]	0.44±0 [a]	0.68±0.01 [f]

4. DISCUSSION

4.1. Composting of solid sludge

During the first two weeks of composting, windrows of all treatments emitted foul odors. These foul odors could be the result of the release of malodorous gases such as ammonia in large quantities. After the first two weeks, the foul odors began to gradually decrease until the 40th day of composting, when they tended to a humus odor. At the end of the composting process, all windrows had lost their foul odor and had an earthy odor. The physical appearances of the solid sludge before and at the end of composting showed that the solid sludge, which had a pasty texture and a brown color before treatment, became dark brown to black, with a powdery soil texture after 60 days of treatment in all four treatment systems. These characteristics observed after treatment are those of mature compost according to Baharuddin et al. [22]. The powdery and granule-like appearance of the resulting compost indicates that the solid sludge, palm stalks, and sawdust used as substrates were degraded during the composting process. The presence of many pores suggests that cellulose and hemicellulose were broken down. This degradation could be attributed to the activity of biodegradative microorganisms (lipolytic, cellulolytic, and lignolytic) present in the windrows during composting Niu and Li [23]. Wathida et al. [24] in their work on the biochemical changes during the composting of oil palm stalks with settling sludge, it was found that in the piles supplemented with red soil as a substrate, the bad odor gradually decreased after the initial period until the 45th day, when it had a more earthy odor. At the end (90th day), all the piles had lost their bad smells, and the composted materials had completely transformed into humus.

4.2. Study of Composting Parameters

4.2.1. Evolution of Windrow Temperature During Treatment

Temperature is an important parameter for indicating microorganism activity, stability, and maturity of the finished product during the composting process. Analysis of variance shows that there is a significant effect of day and treatment on the evolution of windrow temperature during composting. The temperature evolution curves during the composting process show three phases for all four treatments, starting at a temperature of approximately 27°C. A thermophilic phase between day 0 and day 12, which results in a rapid increase in temperature to 56°C. A mesophilic phase between day 12 and day 30, which results in a decrease in temperature between 40°C and 32°C. A maturation phase between day 30 and day 60, during which the temperature varies very little between 31 and 30°C. According to Mukesh et al. [25], temperature changes during composting strongly reflect the metabolic activity of microorganisms. The rapid increase in temperature at the beginning of composting is due to the rapid multiplication of mesophilic microorganisms, which utilize sugars and amino acids readily available in the medium. This process produces heat for their own metabolism [26]. Meanwhile, thermophilic microorganisms continue the process by increasing the temperature more and more. According to Zhong et al. [27], this increase in temperature is crucial for the quality of the compost because the heat kills pathogenic microorganisms and weed seeds present in the substrates to be composted. According to Ramli et al. [28], maximum composting activity can be achieved under thermophilic conditions with a temperature in the range of 50-60°C. The decrease in temperature observed between day 12 and day 30 could be explained by the depletion of organic matter readily available to microorganisms, such as cellulose and hemicellulose. This leads to a decrease in the metabolic activity of microorganisms. The stabilization of temperature around 30°C during the last thirty days of composting reflects the fact that the chemical reactions of biodegradation continue to occur but at a very low intensity, making the remaining organic matter more stable and suitable for plant use [28]. The treatments with the addition of bacteria (T3 and T1) presented the highest temperatures during the composting process (56.03°C and 53.77°C), compared to the treatments without the addition of bacteria (T2 and T4), which recorded temperatures of 47.67°C and 49.22°C. Mukesh et al. [25] found in their work on in-vessel co-composting of food waste using an enriched bacterial consortium, the compost reactor inoculated with a bacterial consortium showed a significant increase in temperature, reaching 68°C in 2 days compared to the non-inoculated reactor. This indicates that the microorganisms could efficiently decompose the organic matter of food waste. Furthermore, treatments with the sawdust substrate exhibited the highest temperatures during composting compared to treatments with the stalk substrate. This can be explained by the fact that the addition of sawdust increases the porosity of the solid sludge compared to the stalks. Consequently, increased porosity promotes oxygen penetration and enhances microbial metabolism, leading to an increase in temperature [29].

4.2.2. Changes in Windrow Moisture Content During Treatment

Humidity is a critical factor in the composting process because it affects microbial activity and the physicochemical properties of the substrate. Analysis of changes in windrow moisture content during composting showed a significant effect of the treatment day on moisture content. The moisture content curves show that all treatments started with a moisture content of approximately 78%. Subsequently, a gradual decline was observed in all treatments throughout the composting period, with the most significant decrease between days 3 and 30. The composting process led to the evaporation of approximately 72% of the water contained in the waste at the beginning of composting. These results are similar to those of Baron et al. [30], who found that thermophilic composting led to the overall evaporation of 60 to 65% of the water contained in the substrate. During the first two weeks of treatment, when composting activity is maximal, the moisture content remained above 50%. As indicated in previous studies, the optimal moisture content for aerobic composting is between 50-60% [31]. The gradual decrease in moisture content is correlated with the rise in temperature and the turning of the windrows during treatment, which leads to water evaporation [22]. Treatments with sawdust substrate (T3 and T4) showed slightly lower moisture contents compared to treatments with stalk substrate (T1 and T2). This could be explained by the fact that the addition of sawdust allows for greater porosity of solid sludge compared to the stalks. Thus, increased porosity promotes oxygen penetration and improves microbial metabolism, which leads to an increase in temperature as well as water evaporation. According to Yaser et al. [32] the addition of sawdust reduces the wet density and the humidity rate, thus promoting waste degradation. Also, treatments with bacterial inoculum (T1 and T3) showed the lowest humidity rates compared to treatments without bacterial inoculum (T4). The low humidity rate obtained at the end of composting is a good indicator of compost quality.

4.2.3. Evolution of Windrow pH During Treatment

Microbial activity largely depends on the pH conditions within the composting environment. Most microorganisms, particularly bacteria, thrive around a neutral pH. Analysis of pH changes during composting indicates a significant effect of both time and treatment. According to the pH curve, all treatments initially exhibit a weakly acidic pH (5.8, 5.8, 6.37, and 6.20 for treatments T1, T2, T3, and T4, respectively). This acidity is attributed to the presence of fatty acids in the solid sludge. At the start of composting, a gradual increase in pH is observed until day 30, reaching values above 8 in all treatments. This rise in pH may be due to ammonia production resulting from the decomposition of proteins and amino acids [33]. After day 30, a gradual decrease in pH was observed, which tended towards neutrality (between 7.17 and 7.5) at the end of the composting process in all treatments. The decrease in pH is likely due to CO^2 emissions from the degradation of organic matter, nitrification, and the formation of low molecular weight fatty acids during composting [33]. The final pH values obtained at the end of composting, varying between 7.17 and 7.5 for all treatments, met the recommended pH standard for good composting (pH < 9) [33]. For optimal composting, a neutral pH has been reported in previous studies [34]. Treatments with sawdust substrate (T3 and T4) exhibited higher pH values compared to treatments with stalks as substrate (T1 and T2). However, treatments with bacterial inoculum (T1 and T3) showed the highest pH levels compared to treatments without bacterial inoculum (T2 and T4). The addition of bacteria likely facilitated a more pronounced decomposition of proteins and amino acids, resulting in increased ammonia production, which elevates the pH of the environment. Similarly, the presence of sawdust may have promoted better proliferation of microorganisms in the windrows, leading to increased decomposition of proteins and amino acids and consequently more ammonia production.

4.2.4. Changes in the Electrical Conductivity of the Windrows During Treatment

The analysis of electrical conductivity indicates a significant effect of day and treatment on its progression. According to the electrical conductivity trend, all treatments initially exhibited a relatively high value of 5.07 mS/cm. The conductivity decreased progressively across all treatments during the composting process compared to day 0. On day 60, the values recorded were 3.44, 2.99, 2.86, and 2.13 mS/cm for treatments T1, T2, T3, and T4, respectively. Notably, sawdust treatments (T3 and T4) showed the lowest electrical conductivity values compared to stalk treatments (T1 and T2). Additionally, the reduction was more significant in treatments with bacterial addition (T1 and T3). The decline in conductivity during composting is atypical and is generally attributed to the reduction of soluble nutrient ions, which are fixed during the rapid proliferation of aerobic microorganisms and subsequently precipitate as insoluble mineral salts or are lost through ammonia volatilization [35]. These electrical conductivity values are slightly below the recommended values by the Compost and Soil Conditioner Quality Standards [36].

4.3. Study of Minerals of Agronomic Interest

A significant increase ($p<0.05$) in nitrogen, phosphorus, and magnesium content was observed in all treatments on the 30th and 60th days of composting compared to day 0. Treatments with the cob substrate plus bacteria (T1) showed increases of 176.72%, 83.76%, and 41.18%, respectively, for nitrogen, phosphorus, and magnesium on day 60. Furthermore, treatments with the cob substrate without bacteria (T2) showed increases of 147.41%, 81.67%, and 35.86%, respectively, for nitrogen, phosphorus, and magnesium on day 60. However, treatments with the sawdust substrate plus bacteria (T3) showed increases of 201.72%, 109.94%, and 46.23%, respectively, for nitrogen, phosphorus, and magnesium at day 60. In addition, treatments with the bacteria-free sawdust substrate (T4) showed the increased rates of 147.98%, 96.85%, and 32.16%, respectively, for nitrogen, phosphorus, and magnesium at day 60. According to Greff et al. [37], the increase in the percentage of total nitrogen during the composting process results from the degradation of proteins in the starting materials under the influence of heat and microorganisms. It can also be assumed that part of the nitrogen increase originates from residues of microorganisms that have multiplied, particularly during the initial phase of the composting process. According to Afanou et al. [38] the decrease in organic matter results in a concentration of nutrients and an increase in the mineral composition of the compost during the composting process. the nitrogen contents obtained at the end of composting meet the compost standard recommended by the Ministry of Agriculture of Thailand, which should be greater than 1% of the dry weight, whereas despite the increase in phosphorus content, the values obtained at the end of composting are below the compost standard recommended by the Ministry of Agriculture of Thailand, which should be greater than 0.5% of the dry weight [24]. On the other hand, the potassium content decreased significantly ($p<0.05$) from the first weeks of composting in all treatments. Potassium levels reached on day 30 the values of 0.84%, 0.73%, 0.69%, and

0.70%, respectively, for treatments T1, T2, T3, and T4. After day 30, potassium content continued to decrease in all treatments, reaching values of 0.78%, 0.53%, 0.47%, and 0.244%, respectively, for treatments T1, T2, T3, and T4 on day 60. This decrease could be explained by the leaching of potassium during watering, as the leachate was not collected to be returned to the windrows. Despite these potassium losses, the values obtained at the end of composting in all treatments, except for treatment T4, meet the compost standard recommended by the Ministry of Agriculture of Thailand, which should be greater than 0.5% of the dry weight [24]. Thus, treatments with the addition of bacteria have the highest macroelement contents compared to treatments without the addition of bacteria. This could be due to the fact that the inoculation of bacteria increased the intensity of waste degradation, leading to an increase in mineral elements. Overall, treatments with oil palm stalks had slightly higher macronutrient contents compared to treatments with sawdust. With a powdery texture, sawdust may have promoted mineralization intensity more than stalks. According to Yaser et al. [32], sawdust retains ammonia, thus increasing nitrogen content.

5. CONCLUSION

The objective of this study was to contribute to reducing environmental pollution from palm oil agro-industries in Cameroon through improved waste management practices for sustainable production. The results indicated that the biostimulation method combined with bio-increase used for treating solid sludge from palm oil extraction facilitated the mineralization of the sludge and the elimination of foul odors it emitted. The evolution of physicochemical parameters during composting demonstrated optimal trends for microbial metabolic activity, enabling effective mineralization of organic matter and producing a stable, mature, and high-quality final product after 60 days. The type of substrate and the addition of bacterial inoculum influenced composting parameters and the minerals of agronomic interest, thereby affecting the quality of the resulting compost. Treatments with sawdust showed slightly higher mineralization rates than those with oil palm stalks. Additionally, treatments with bacterial inoculum achieved the highest mineralization rates. All treatments resulted in mature compost after 60 days, meeting the standards set by the Compost and Soil Conditioner Quality Standard (HKORC) and containing significant nutrients aligned with the United States Environmental Protection Agency (USEPA) standards for use as a soil amendment and fertilizer, without phytotoxicity.

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