Scientific Research Publishing

Food and Nutrition Sciences, 2026, 17(9), 834-857
https://www.scirp.org/journal/fns
ISSN Online: 2157-9458
ISSN Print: 2157-944X

Evaluation of the Effect of Using Sewage Sludge Compost as an Organic Soil Amendment on the Microbiological Quality of Bell Peppers (*Capsicum annuum* L.) in the Tropical Environment of Côte d'Ivoire

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How to cite this paper: Taho, B.R., Konan, K.A., Kouassi, K.A. and Kouassi, N.J. (2026) Evaluation of the Effect of Using Sewage Sludge Compost as an Organic Soil Amendment on the Microbiological Quality of Bell Peppers (*Capsicum annuum* L.) in the Tropical Environment of Côte d'Ivoire. *Food and Nutrition Sciences*, **17**, 834-857.
https://doi.org/10.4236/fns.2026.179053

Received: July 15, 2026
Accepted: September 19, 2026
Published: September 22, 2026

Abstract

Introduction: The agricultural valorization of faecal sludge-derived composts represents a promising strategy for improving soil fertility and promoting sustainable waste management in sub-Saharan Africa. However, their use in crop production requires prior assessment of their agronomic characteristics and microbiological safety to limit potential risks associated with the transfer of undesirable microorganisms to edible crops. **Objective:** This study aimed to evaluate the physicochemical and microbiological characteristics of faecal sludge-derived composts before field application and to assess the effects of compost type, application rate, and planting density on the microbiological quality of sweet pepper (*Capsicum annuum* L.) fruits produced under tropical field conditions in Daloa, Côte d'Ivoire. **Materials and Methods:** Four composts produced from faecal sludge collected at different sites, including Bédiala Road landfill (CB), Bra Kanon (CBK), Garage neighborhood (CG), and Soleil neighborhood (CS), were characterized before application based on physicochemical parameters (pH, C/N ratio, organic matter, and nutrient contents) and microbiological indicators. Their effects were evaluated in comparison with mineral fertilization (NPK). At a fixed compost application rate of 30 t/ha, three planting densities (40 × 50, 50 × 50, and 50 × 60 cm) were

evaluated. In a second experiment, planting density was fixed at 50 × 50 cm and compost application rates of 20, 30, and 40 t/ha were assessed. Microbiological analyses of sweet pepper fruits included aerobic mesophilic bacteria (AMB), total and thermotolerant coliforms, yeasts and molds, coagulase-positive staphylococci, *Escherichia coli*, and *Salmonella* spp., according to ISO standards. Data were analyzed using analysis of variance (ANOVA) followed by Tukey's multiple comparison test at a 5% significance level. **Results:** After four months of composting, all composts showed physicochemical characteristics consistent with satisfactory stabilization, with pH values ranging from 7.11 to 7.30 and C/N ratios between 16.2 and 20.2. Their organic matter contents (22.7% - 29.5%) and nutrient composition indicated valuable agronomic potential. Microbiologically, *Salmonella* spp. was not detected and *Escherichia coli* levels remained below the detection limit (<1 CFU/g) in all composts. Following field application, microbial loads in sweet pepper fruits varied according to compost type, planting density, and application rate. Aerobic mesophilic bacteria loads ranged from $57.50 \pm 1.58 \times 10^4$ to $955.00 \pm 10.90 \times 10^4$ CFU/g, while total coliforms reached a maximum of $8.75 \pm 0.12 \times 10^4$ CFU/g. Thermotolerant coliforms, yeasts and molds, and coagulase-positive staphylococci also showed significant variations among treatments ($p < 0.05$). However, *E. coli* remained below the detection limit (<1 CFU/g) and Salmonella spp. was not detected in any of the analyzed fruits, regardless of compost type, application rate, or planting density. **Conclusion:** The findings indicate that the use of faecal sludge-derived composts influenced the levels of several hygiene and spoilage indicators in sweet pepper fruits, while no contamination by the major enteric pathogens investigated was detected. Under controlled composting conditions and appropriate agricultural practices, these composts may represent a promising alternative to mineral fertilization for sweet pepper production. Nevertheless, appropriate monitoring of microbiological quality remains necessary to ensure the safety of crops fertilized with these organic amendments.

Keywords

Capsicum annuum L., Faecal Sludge Compost, Microbiological Quality, Food Safety, Hygiene Indicator Microorganisms

1. Introduction

Vegetable crops play a vital role in global food and nutritional security due to their significant contribution to the intake of essential micronutrients, including vitamins, minerals, and various bioactive compounds. Regular consumption is associated with improved dietary quality and a reduced risk of several chronic non-communicable diseases [1]-[3]. However, in tropical regions particularly in sub-Saharan Africa low soil fertility is a major constraint limiting the sustainable intensification of vegetable production [4]. To boost agricultural yields, producers rely heavily on mineral fertilizers because of their apparent short-term effective-

ness. Yet, prolonged and sometimes improper use of these fertilizers can disrupt soil physicochemical and biological properties and lead to the gradual accumulation of certain contaminants, notably heavy metals [5]-[8]. Furthermore, the high cost of these inputs and their limited accessibility for many producers drive the search for more sustainable organic alternatives.

In this context, the agricultural valorization of organic waste particularly composts derived from fecal sludge represents a promising approach within the framework of a circular economy and sustainable resource management. These soil amendments constitute a significant source of organic matter and nutrients capable of enhancing soil fertility and crop productivity. However, their use in agriculture raises major concerns regarding food safety. Indeed, fecal sludge can contain a variety of microorganisms of fecal origin (enteric bacteria, viruses, and parasites), the persistence of which depends heavily on the treatment conditions applied [9].

Among vegetable crops, the bell pepper (*Capsicum annuum* L.) is of particular interest due to its economic and nutritional importance. It is a significant source of bioactive compounds notably carotenoids, phenolic compounds, and vitamin C which are associated with recognized antioxidant properties [10]-[12]. However, its frequent consumption in fresh or minimally processed forms also makes it susceptible to microbiological contamination. Fresh vegetables can become contaminated throughout the production chain via soil, irrigation water, cultivation practices, and, in particular, the organic amendments used [13]. Several studies have shown that plant surfaces can support the survival of fecal indicator microorganisms and pathogens under favorable environmental conditions, especially in the presence of moisture and organic matter [14] [15]. Other studies have also revealed high loads of indicator microorganisms and pathogens in septage (fecal sludge), including bacteria belonging to the coliform group, pathogenic Enterobacteriaceae such as *Salmonella* spp., and opportunistic bacteria such as *Staphylococcus aureus* [7] [16]. Consequently, assessing the microbiological quality of crops grown using these amendments is a critical issue for ensuring food safety and promoting sustainable agricultural reuse.

In Côte d'Ivoire, particularly in the Daloa region, the agricultural use of composts derived from fecal sludge collected at urban dumpsites is an increasingly common practice in market gardening systems. This practice is driven by the local availability of these organic materials and their agronomic value. However, the variability of their microbiological composition and the lack of systematic monitoring regarding their sanitary safety raise questions about the quality of the resulting produce. Despite the growing prevalence of this practice, scientific data remain limited regarding the microbiological impact of using fecal sludge composts on vegetables intended for human consumption under African tropical conditions.

Thus, this study aims to assess the impact of using septage sludge composts on the microbiological quality of bell peppers (*Capsicum annuum* L.) grown in the Daloa region of Côte d'Ivoire. More specifically, it involves determining the mi-

crobial load of the peppers by enumerating total aerobic mesophilic flora, yeasts and molds, coliforms, and *Escherichia coli*, as well as by screening for pathogenic microorganisms such as *Salmonella* spp. and *Staphylococcus aureus*. This approach will make it possible to evaluate the microbiological safety of peppers produced using septage sludge composts and to assess the health risks potentially associated with their use as organic amendments in tropical agriculture.

2. Materials and Methods

2.1. Description of the Study Area

The study was conducted in Sapia, a village of approximately 1640 inhabitants located in the Daloa region of central-western Côte d'Ivoire (coordinates 6˚54′01″N, 6˚24′10″W) (Figure 1). This area is part of the Haut-Sassandra agricultural basin, characterized by intensive crop production and an abundant supply of organic matter derived from urban waste. Daloa is situated approximately 141 km from Yamoussoukro and 383 km from Abidjan. It is one of the country's major urban centers, with a population estimated at 1,430,960 inhabitants according to the 2015 General Census of Population and Housing (RGPH).

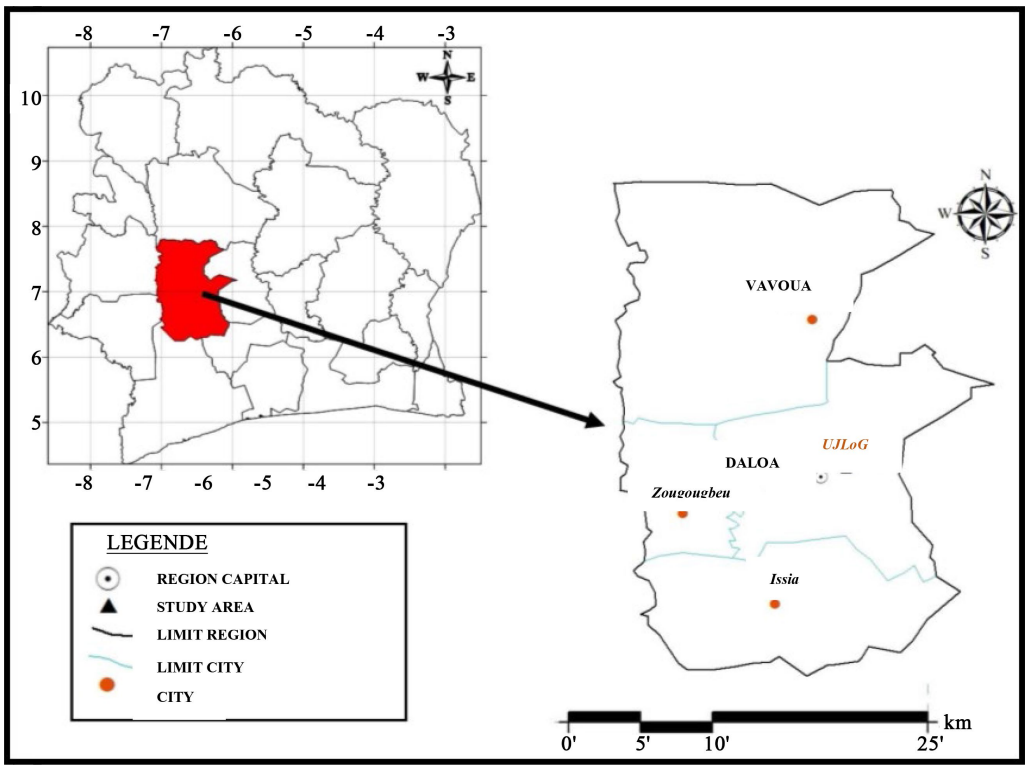

Figure 1. Study area.

2.2. Plant Material

The plant material used was sweet pepper (*Capsicum annuum* L., Goliath F1 hybrid), selected for its productivity and adaptation to local agro-ecological conditions.

2.3. Preparation of Fecal Sludge Compost

The sewage sludge used in this study was collected from various landfills in the city of Daloa (Ivory Coast) between December 2023 and January 2024. Samples were collected during eight sampling campaigns, directly as sewage trucks were unloading, using a motorized tricycle. A total of twenty-four sludge samples were collected and then transported to the experimental site to begin the composting process (Figure 2).

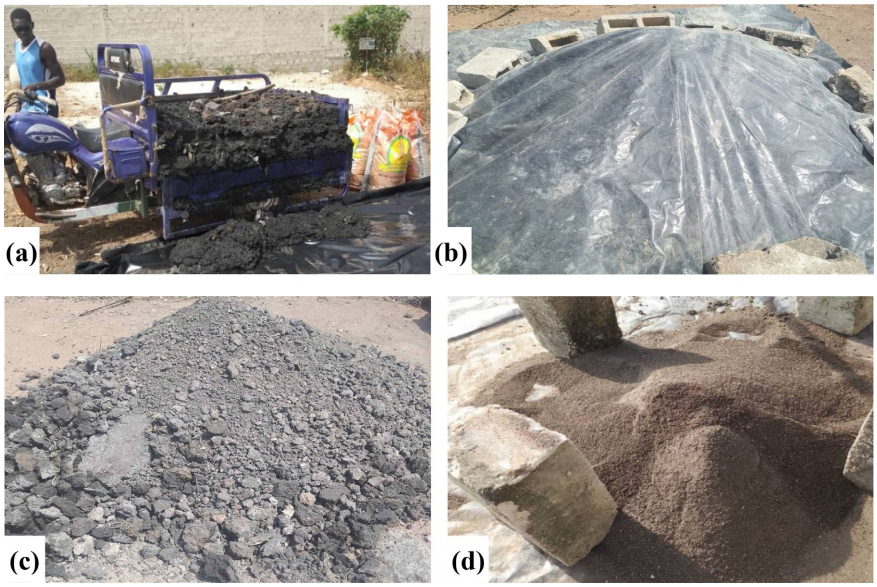

Figure 2. Sewage sludge composting process. (a) Tricycle transportation of faecal sludge; (b) Faecal sludge stockpiling; (c) Mature dehydrated compost; (d) Sieved mature compost.

Composting was conducted using the windrow method, with strict separation of the sludge according to its site of origin in order to produce differentiated composts. Four types of compost were thus produced: compost from the Bédiala Road landfill (CB), compost from the Bra Kanon landfill (CBK), compost from the Garage neighborhood landfill (CG), and compost from the Soleil neighborhood landfill (CS). A commercial NPK mineral fertilizer (15-15-15) was also used as the control treatment in the agronomic experiment. No physicochemical or microbiological analyses were performed on the NPK fertilizer, as it was used only as a reference treatment in the field experiment.

The composting process was maintained for a period of four months. The temperature of the compost piles was monitored regularly to assess the progression of the organic matter degradation process. Initial temperatures, ranging from 65 to 75˚C, gradually decreased during composting, reaching values between 25 and 37˚C during the maturation phase, indicating a gradual stabilization of the composted material.

The maturity of the resulting composts was assessed using physicochemical and microbiological indicators, notably pH, the carbon-to-nitrogen (C/N) ratio, the stabilization of organic matter, and the hygienic quality of the final products. Ac-

cording to [17], a C/N ratio below 20 - 25 is a commonly used indicator for assessing the stabilization of compost. Furthermore, the absence of major pathogenic microorganisms, particularly Salmonella spp., combined with low levels of microorganisms indicative of fecal contamination, is an important criterion for evaluating its suitability for agricultural use.

After the maturation phase, the composts were dried and then screened to achieve a uniform particle size, making them easier to handle and apply to the experimental plots.

2.4. Experimental Setup and Crop Treatments

The experiment was conducted at a vegetable farm using a block design consisting of six experimental blocks. Each block comprised 15 elementary plots of 10 m^2 (10 m × 1 m), arranged in three rows of five plots. The individual plots within the same block were spaced 2 m apart to minimize interference between treatments, while a distance of 3 m separated the experimental blocks.

The area of a block was approximately 540 m^2 (60 × 9 m), including the experimental plots, aisles, and borders (1 m). The five plots in each row corresponded to the five fertilizer treatments: four composts derived from sewage sludge. Compost from the Bédiala Road landfill (CB), compost from the Bra Kanon landfill (CBK), compost from the Garage neighborhood landfill (CG), compost from the Soleil neighborhood landfill (CS), and the control (T) fertilized with NPK mineral fertilizer (15/15/15).

The study was organized into two separate trials.

The first trial aimed to evaluate the effect of planting density on pepper quality. Three blocks were dedicated to this trial, each corresponding to a different planting density, namely: D1 = 40 × 50 cm; Block 2: D2 = 50 × 50 cm; and Block 3: 50 × 60 cm (Figure 3). For this trial, the compost application rate was kept constant at 30 t/ha across all treatments.

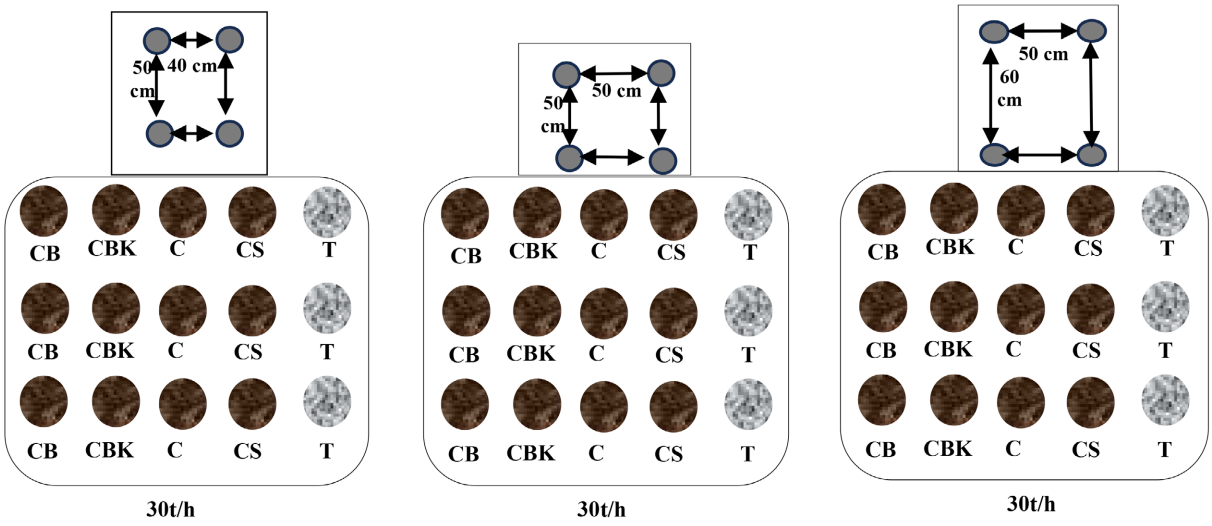

Figure 3. Blocs expérimentaux avec variation de densité et fixation de dose à 30T/ha.

The objective of the second experiment was to evaluate the effect of the compost application rate. Three additional plots were established with a planting density of 50 × 50 cm. The three application rates studied were 20 T/h, 30 T/h, and 40 T/h, each applied in a separate block (Figure 4). The five fertilizer treatments (CB, CBK, CS, and NPK) were maintained in each of the blocks.

Thus, each block comprised three rows of five plots, ensuring an identical distribution of fertilizer treatments, while the planting density or compost application rate varied according to the specific objective of each trial.

Depending on the planting density, each basic plot contained 50 plants (D1), 40 plants (D2), and 33 plants (D3), corresponding to 750, 600, and 495 plants per block, respectively, for a total of 1845 plants in the first trial. For the second trial, the density was set at D2 (50 × 50 cm), or 40 plants per plot across 15 plots. This resulted in 1800 plants for the second trial.

In total, 3645 plants were recorded for this study.

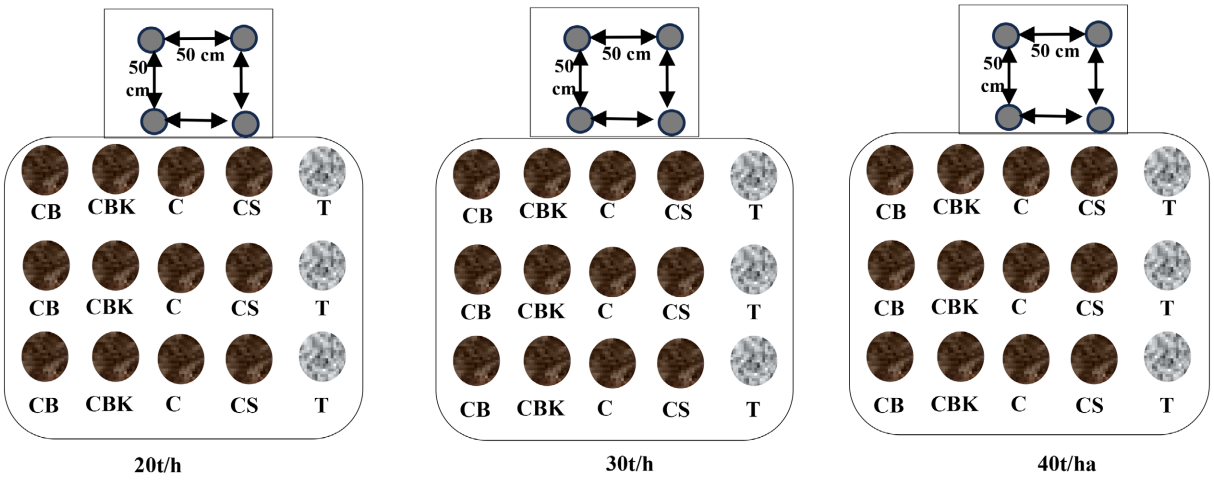

Figure 4. Blocs expérimentaux avec variation et fixation de la odes et de densité 50 × 50 cm.

2.5. Plot Treatments

The fertilization treatments in both trials were applied to the respective experimental plots at a rate of at least 30 plants per plot. Compost was applied when the ridges were formed, 21 days before transplanting the pepper plants, by evenly spreading the weighted doses of compost over the surface of the relevant experimental plots and incorporating them into the top 20 - 25 centimeters of soil while forming the ridges. The interval between compost application and the start of harvest was 91 days. Irrigation was carried out using water from a well, and a watering can was used for this purpose.

2.6. Sample Collection

Pepper fruits (*Capsicum annuum* L.) were harvested at the stage of physiological maturity, after irrigation was discontinued, in order to assess their microbiological quality. Samples were collected at random from each of the experimental plots (Figure 5).

Figure 5. Fruit Production and Harvesting. (a) plant in production; (b) bell peppers.

Each fertilization treatment was represented by three replicates, corresponding to the three rows in each block. For each replicate, three fruits were selected at random and then ground together to form a composite sample representative of the plot.

Thus, each treatment yielded three composite samples per block, or one sample per replicate. Since each block comprised five fertilization treatments, 15 composite samples were obtained. In total, the six experimental blocks yielded 90 composite samples (15 samples per block × 6 blocks) for microbiological analysis.

The purpose of preparing a composite sample from three fruits was to obtain a representative sample from each replicate while reducing variability due to individual differences among the fruits.

Pour la combinaison spécifique correspondant à une densité de plantation de 50 × 50 cm associée à une dose d'application de compost de 30 t/ha, évaluée dans deux blocs expérimentaux, la caractérisation microbiologique a été réalisée à partir des échantillons de répétition correspondants générés dans ces blocs. Ces échantillons ont été pris en compte conformément au plan expérimental pour l'analyse statistique, la parcelle de répétition étant considérée comme l'unité expérimentale dans l'ANOVA.

After collection, the samples were handled under strict aseptic conditions using disposable gloves and sterile equipment. They were then placed in sterile Stomacher®-type bags, transported to the laboratory in an insulated cooler maintained at 4˚C, and stored until analysis, which was performed within a maximum of 24 hours.

2.7. Microbiological Analyses

Microbiological analyses were conducted in accordance with current ISO and AFNOR standards to assess the hygienic and sanitary quality of bell peppers. The microorganisms used as indicators of hygiene and spoilage included total mesophilic aerobic flora (TMAF), total and thermotolerant coliforms, Escherichia coli, as well as yeasts and molds. Testing was also conducted for the main pathogenic microorganisms likely to compromise the food safety of the peppers, notably Sal-

monella spp. and coagulase-positive staphylococci.

Stock suspensions were prepared in accordance with the AFNOR NF V08-010-2 (1996) standard. To this end, 25 g of each composite sample was homogenized in 225 mL of buffered peptone water, followed by successive decimal dilutions to perform the various microbiological analyses. All microbiological analyses were performed exclusively on bell peppers (*Capsicum annuum* L.), which constituted the sole plant matrix studied. This methodological approach ensured the homogeneity of the experimental samples as well as the reliability of the microbiological comparisons made between the different treatments.

2.7.1. Enumeration of Microorganisms Indicative of Hygiene and Spoilage

- **Total mesophilic aerobic flora (TMAF)**

The total mesophilic aerobic flora was counted in accordance with ISO 4833-1:2013 by deep plating on Plate Count Agar (PCA). After incubation at 30˚C for 72 hours, characteristic colonies were counted, and the results were expressed in colony-forming units per gram of sample (CFU/g).

- **Escherichia coli**

Escherichia coli was enumerated in accordance with ISO 16649-3:2015 by deep plating on a chromogenic medium. The plates were incubated at 44˚C for 24 h, after which characteristic colonies were counted and expressed in CFU/g.

- **Yeasts and molds**

Yeasts and molds were quantified according to ISO 21527-1:2008 by surface plating on Sabouraud agar supplemented with chloramphenicol. Incubation was carried out at 25˚C for 72 hours, followed by counting of fungal colonies expressed in CFU/g.

- **Total and thermotolerant coliforms**

Total and thermotolerant coliforms were enumerated in accordance with ISO 4832:2006 on Violet Red Bile Lactose (VRBL) agar. Incubation was performed at 37˚C for total coliforms and at 44˚C for thermotolerant coliforms.

2.7.2. Screening and Enumeration of Pathogenic Microorganisms

- **Salmonella spp.**

Screening for Salmonella spp. was performed in accordance with ISO 6579-1:2017. The procedure included a pre-enrichment step in buffered peptone water, followed by selective enrichment in Rappaport-Vassiliadis broth, and then isolation on Hektoen agar. The results were reported as the presence or absence of Salmonella spp. in the analyzed sample.

- **Coagulase-positive staphylococci**

Coagulase-positive staphylococci were enumerated in accordance with ISO 6888-1 and ISO 6888-2, which describe the horizontal method for enumerating coagulase-positive staphylococci (Staphylococcus aureus and related species). The count was performed on Baird-Parker agar after incubation at 37˚C for 24 hours, and the results were expressed in CFU/g.

2.8. Literal Calculation of the Microbial Load

Microbiological results were reported in accordance with the recommendations of international standards regarding the enumeration of microorganisms in food matrices.

Microbial loads were expressed in colony-forming units per gram of fresh material (CFU/g). The number of microorganisms was calculated using the following standardized equation (1):

$$N = \frac{\sum C}{V \times \left(n_1 + 0.1 n_2\right) \times d} \quad (1)$$

where C denotes the microbial concentration (CFU/g), ∑C is the sum of colonies counted on two consecutive selected dilutions, V is the inoculated volume (mL), n_1 is the number of plates selected at the first dilution, n_2 is the number of plates selected at the next dilution, and d is the dilution factor corresponding to the first selected dilution.

Only plates with a colony count falling within the validity ranges recommended by ISO standards were taken into account. It was difficult to find specific microbiological criteria in Côte d'Ivoire. The European Commission's criteria applicable to the manufacturing, preparation, cutting, or simple handling of "open-cut" food products in workshops or stores were therefore applied. The guidelines and measured standards were compared to the thresholds set by current European legislation (Regulation (EU) 2019/1009). Specifically, GAM at 10^6 CFU/g; yeast and mold (10^6 CFU/g); Salmonella: Abs = absence in a 25-gram sample; *E. coli* must not exceed 100 CFU/g; the majority of pathogenic bacteria must be absent.

2.9. Statistical Analyses

The collected data were analyzed using Excel. Statistical analyses were performed using appropriate software (Minitab 18.1), ensuring the validity of the statistical inferences. The data were expressed as mean ± standard deviation (n = 3). An analysis of variance (ANOVA) was used to compare means at a significance level of 5% ($p < 0.05$). Comparisons of means were performed using Tukey's test when the effect was significant ($p < 0.05$).

3. Results

3.1. Physicochemical Characteristics of Each Compost Prior to Application

The physicochemical characteristics of each compost prior to application are listed in the table below:

The physicochemical characteristics of the composts are presented in Table 1. The pH values were relatively consistent across the different composts, ranging from 7.11 to 7.30 (Table 1). Organic carbon contents ranged from 13.19% to 17.17%, while total nitrogen contents ranged from 0.76% to 0.98%.

The carbon-to-nitrogen (C/N) ratio ranged from 16.2 to 20.2, with the highest

value observed for the CBK compost and the lowest for the CG compost. Organic matter content ranged from 22.7% to 29.5%. Regarding mineral elements, available phosphorus levels ranged from 2.78 to 3.20 ppm, while potassium, calcium, and magnesium concentrations varied depending on the origin of the composts.

Table 1. Physicochemical characteristics of each compost prior to application.

Physicochemical characteristics	CB	CBK	CG	CS
PH	07.30	07.12	07.24	07.11
C (%)	17.17	16.96	13.19	13.94
Nt (%)	0.98	0.84	0.81	0.76
C/N	17.50	20.20	16.20	18.40
M.O (%)	29.50	29.20	22.7	24.00
Pass (ppm)	03.20	02.86	2.82	02.78
K^+ (cmol·kg^{-1})	01.24	01.38	1.62	01.72
Ca^{2+} (cmol·kg^{-1})	01.23	01.13	0.90	0.88
Mg^{2+} (cmol·kg^{1})	0.31	0.28	0.23	0.22

Overall, the composts exhibited variable physicochemical characteristics depending on their origin, with pH, carbon, nitrogen, and mineral element values that were relatively similar across the different treatments.

3.2. Microbiological Characteristics of Each Compost Prior to Application

The microbiological characteristics of each compost prior to application are recorded in the table below. The microbiological characteristics of the various composts prior to application are presented in Table 2. The results show variation in microbial loads depending on the origin of the composts. The Mesophilic Aerobic Flora (MAB) ranged from 3.11×10^2 to 9.63×10^2 CFU/g, with the highest value recorded for the CG compost. Total coliforms ranged from 1.28×10^2 to 2.81×10^2 CFU/g, while thermotolerant coliforms ranged from 0.30×10^2 to 0.71×10^2 CFU/g.

Yeasts and molds were detected in all composts, with levels ranging from 0.16×10^2 to 1.53×10^2 CFU/g. Coagulase-positive staphylococci also varied among the

Table 2. Microbiological characteristics of each compost prior to application.

Organic amendment	Indicator bacteria for hygiene and spoilage					Pathogenic germs	
	MAB 10^2 UFC/g	Total coli-forms·10^2 UFC/g	Thermo Co-liforms·10^2 UFC/g	Yeast/Mold·10^2 UFC/g	*E. coli* (·10^2 UFC/g)	Staph (.10^2 UFC/g)	Salmo
CB	3.11 ± 08.21	1.62 ± 0.14	0.45 ± 0.77	0.39 ± 0.02	<1	0.71 ± 0.01	Absent
CBK	08.57 ± 0.15	1.28 ± 0.12	0.30 ± 0.01	0.16 ± 0.03	<1	1.23 ± 0.02	Absent
CG	9.63 ± 0.34	2.61 ± 0.32	0.71 ± 0.87	0.26 ± 0.02	<1	2.87 ± 0.01	Absent
CS	5.73 ± 1.05	2.81 ± 0.26	0.43 ± 0.76	1.53 ± 0.01	<1	0.89 ± 0.05	Absent

compost samples, with concentrations ranging from 0.71×10^2 to 2.87×10^2 CFU/g. In contrast, *Escherichia coli* was below the limit of detection (<1 CFU/g) in all compost samples analyzed, while *Salmonella* spp. was not detected in any sample.

3.3. Microbial Loads (×10⁴ CFU/g) of Sweet Pepper (*Capsicum annuum* L.) Fruits under Different Planting Densities with Compost Application Fixed at 30 t/ha

3.3.1. Effect of Fertilizer Type on Microbial Loads at a Planting Density of 40 × 50 cm and a Fixed Application Rate of 30 t/ha

1) Hygiene and Deterioration Microflora

An analysis of the flora indicative of hygiene and spoilage reveals that the type of fertilization has a significant impact on the microbiological quality of bell peppers.

The 40 × 50 cm planting density significantly influenced the loads of hygiene indicator and spoilage-related microorganisms in sweet pepper fruits. Aerobic mesophilic bacteria (AMB) showed marked variability among treatments, with values ranging from $80.25 \pm 1.24 \times 10^4$ CFU/g under the NPK treatment to $517.50 \pm 5.97 \times 10^4$ CFU/g under compost CS, indicating a higher proliferation of aerobic mesophilic microorganisms under the latter treatment.

Total coliforms also exhibited significant differences among treatments. The highest load was recorded with compost CS ($2.78 \pm 0.05 \times 10^4$ CFU/g), whereas compost CBK showed the lowest value ($1.14 \pm 0.09 \times 10^4$ CFU/g), which was comparable to that observed under NPK fertilization ($1.15 \pm 0.32 \times 10^4$ CFU/g). Thermotolerant coliform loads ranged from $0.24 \pm 0.66 \times 10^4$ CFU/g under NPK to $2.14 \pm 0.09 \times 10^4$ CFU/g under compost CB, with significant differences among treatments ($p = 0.01$) (Table 3).

The fungal flora, represented by yeasts and molds, was also significantly affected by the applied treatments ($p = 0.02$). The recorded loads ranged from 0.95

Table 3. Microbial load (×10⁴ CFU/g) of bell peppers (*Capsicum annuum* L.) as a function of planting density of 40 × 50 cm.

Composts Fertilizer	Indicator bacteria for hygiene and spoilage						Pathogenic germs	
	Fixed ap-plication rate	MAB 10^4 UFC/g	Total coliforms 10^4 UFC/g	Thermo Coliforms 10^4 UFC/g	Yeast/Mold 10^4 UFC/g	*E. coli*	Staph 10^4 UFC/g	Salmo
CB	**30 T/ha**	95.25 ± 10.37^{c}	2.64 ± 0.09^{a}	2.14 ± 0.09^{a}	1.50 ± 0.08^{bc}	<1	3.07 ± 0.05^{ab}	Absent
CBK	**30 T/ha**	92.50 ± 5.5^{c}	1.14 ± 0.09^{b}	0.68 ± 0.05^{c}	3.00 ± 0.08^{a}	<1	2.77 ± 0.05^{bc}	Absent
CS	**30 T/ha**	517.50 ± 5.97^{a}	2.78 ± 0.05^{a}	0.89 ± 0.08^{b}	2.88 ± 0.05^{b}	<1	3.34 ± 0.10^{a}	Absent
CG	**30 T/ha**	289.00 ± 10.03^{b}	0.83 ± 0.09^{c}	0.50 ± 0.08^{c}	0.95 ± 0.01^{c}	<1	1.47 ± 0.05^{c}	Absent
NPK	**30 T/ha**	80.25 ± 1.24^{d}	1.15 ± 0.32^{b}	0.24 ± 0.66^{d}	0.98 ± 0.21^{c}	<1	1.19 ± 0.10^{d}	Absent

Values are expressed as mean ± standard deviation (n = 3). Values followed by different letters within the same column are significantly different at the 5% significance level (ANOVA, $p < 0.05$). Thermo: Thermotolerant; Salomo: Salmonella; Staph: Staphylococcus aureus; MAB: Mesophilic Aerobic Bacteria. *E. coli*: < 1 CFU/g indicates a value below the limit of detection. Salmonella: Abs = not detected in a 25-g sample.

± 0.01 × 10^4 CFU/g under compost CG to 3.00 ± 0.08 × 10^4 CFU/g under compost CBK. Overall, composts CBK and CS promoted the highest fungal loads, whereas compost CG showed a value comparable to that of the NPK treatment (0.98 ± 0.21 × 10^4 CFU/g), with no significant difference observed (p = 0.01).

In contrast, *Escherichia coli* levels remained below the detection limit (<1 CFU/g) for all treatments, indicating the absence of detectable contamination by this fecal indicator microorganism in harvested sweet pepper fruits.

2) Pathogenic flora

Coagulase-positive staphylococci loads also varied significantly among the applied treatments (p = 0.01), with values ranging from 1.19 ± 0.10 × 10^4 CFU/g under the NPK treatment to 3.34 ± 0.10 × 10^4 CFU/g under compost CS. The value recorded under compost CB (3.07 ± 0.05 × 10^4 CFU/g) was comparable to that observed under compost CS, with no significant difference between these two treatments (Table 3).

Furthermore, no *Salmonella* spp. were detected in the analyzed sweet pepper fruits, regardless of the fertilization treatment applied. Similarly, *Escherichia coli* concentrations remained below the detection limit (<1 CFU/g) in all analyzed samples. Given the consistent absence of these two fecal contamination indicator microorganisms, *E. coli* and *Salmonella* spp. will not be further discussed in the following sections.

3.3.2. Effect of Fertilizer Type on Microbial Loads at a Planting Density of 50 × 50 cm and a Fixed Application Rate of 30 t/ha

The 50 × 50 cm planting density also influenced the levels of hygiene indicator and spoilage-related microorganisms in sweet pepper fruits, with variations observed depending on the type of compost applied.

1) Flora Indicative of Hygiene and Deterioration

Aerobic mesophilic bacteria (AMB) loads varied significantly among treatments (p = 0.01), with values ranging from 57.5 ± 1.58 × 10^4 CFU/g under compost CS to 496.67 ± 3.39 × 10^4 CFU/g under compost CG (Table 4). Except for compost CS, which showed a slightly lower load than the mineral NPK treatment (80.25 ± 1.24 × 10^4 CFU/g), faecal sludge-derived composts generally resulted in higher AMB levels than mineral fertilization, with significant differences observed among treatments.

Total coliforms also showed significant variations (p = 0.03), with the highest load recorded under compost CS (4.88 ± 0.02 × 10^4 CFU/g) and the lowest value under the NPK treatment (1.25 ± 0.08 × 10^4 CFU/g). A similar trend was observed for thermotolerant coliforms, with loads ranging from 0.47 ± 0.78 × 10^4 CFU/g under NPK to 1.54 ± 0.16 × 10^4 CFU/g under compost CB.

The fungal flora, represented by yeasts and molds, was also significantly affected by the applied treatments (p = 0.02). The recorded loads ranged from 1.60 ± 0.14 × 10^4 CFU/g under NPK to 2.51 ± 1.27 × 10^4 CFU/g under compost CS, which exhibited the highest fungal load. In contrast, Escherichia coli levels remained below the detection limit (<1 CFU/g) for all treatments.

2) Pathogenic flora

Compost-based treatments generally showed higher levels of coagulase-positive staphylococci compared with mineral fertilization. Indeed, coagulase-positive staphylococci loads differed significantly among treatments ($p = 0.01$), with values ranging from $1.10 \pm 0.12 \times 10^4$ CFU/g under the NPK treatment to $3.50 \pm 1.03 \times 10^4$ CFU/g under compost CG (Table 4).

Table 4. Microbial loads ($\times 10^4$ CFU/g) of bell peppers (*Capsicum annuum* L.) as a function of planting density of 50 × 50 cm.

Fertilizer	Fixed application rate	Indicator bacteria for hygiene and spoilage					Pathogenic germs	
		MAB 10^4 UFC/g	Total coliforms 10^4 UFC/g	Thermo Coliforms 10^4 UFC/g	Yeast/Mold 10^4 UFC/g	*E. coli*	Staph 10^4 UFC/g	Salmo
CB	**30 T/ha**	401.16 ± 3.88^b	2.26 ± 0.01^c	1.54 ± 0.16^a	1.93 ± 0.12^b	<1	1.55 ± 0.20^c	Absent
CBK	**30 T/ha**	185.75 ± 1.40^{ab}	2.82 ± 0.01^c	1.03 ± 0.18^b	1.61 ± 0.11^c	<1	2.67 ± 0.90^b	Absent
CG	**30 T/ha**	496.67 ± 3.39^a	3.06 ± 0.03^b	1.07 ± 0.87^b	1.62 ± 0.03^c	<1	3.50 ± 1.03^a	Absent
CS	**30 T/ha**	57.50 ± 1.58^d	4.88 ± 0.02^a	1.44 ± 0.76^a	2.51 ± 1.27^a	<1	1.30 ± 0.86^d	Absent
NPK	**30 T/ha**	80.25 ± 1.24^c	1.25 ± 0.08^d	0.47 ± 0.78^c	1.60 ± 0.14^d	<1	1.10 ± 0.12^d	Absent

Values are expressed as mean ± standard deviation (n = 3). Values followed by different letters within the same column are significantly different at the 5% significance level (ANOVA, $p < 0.05$). Thermo: Thermotolerant; Salomo: Salmonella; Staph: Staphylococcus aureus; MAB: Mesophilic Aerobic Bacteria. *E. coli*: < 1 CFU/g indicates a value below the limit of detection. Salmonella: Abs = not detected in a 25-g sample.

3.3.3. Effect of Fertilizer Type on Microbial Loads at a Planting Density of 50 × 60 cm and a Fixed Application Rate of 30 t/ha

1) Hygiene and Decay Microflora

Aerobic mesophilic bacteria (AMB) loads varied significantly among the applied treatments ($p = 0.01$), with values ranging from $153.33 \pm 8.95 \times 10^4$ CFU/g under the NPK treatment (control) to $955.00 \pm 42.03 \times 10^4$ CFU/g under compost CG (Table 5).

Total coliforms also showed significant differences among treatments ($p = 0.01$). The recorded loads ranged from $0.77 \pm 0.05 \times 10^4$ CFU/g under compost CB to $8.75 \pm 0.50 \times 10^4$ CFU/g under compost CS, followed by compost CG, which showed a load of $7.50 \pm 0.10 \times 10^4$ CFU/g.

Thermotolerant coliform loads also varied significantly ($p = 0.01$), ranging from $0.05 \pm 0.01 \times 10^4$ CFU/g under compost CBK to $2.25 \pm 0.10 \times 10^4$ CFU/g under compost CG.

The fungal flora, represented by yeasts and molds, was also significantly affected by the applied treatments ($p = 0.02$), with loads ranging from $0.67 \pm 0.18 \times 10^4$ CFU/g under the NPK treatment to $1.47 \pm 0.24 \times 10^4$ CFU/g under compost CBK.

2) Pathogenic flora

Coagulase-positive staphylococci loads varied significantly among treatments ($p = 0.01$), with values ranging from $1.39 \pm 0.08 \times 10^4$ CFU/g under compost CG to $3.48 \pm 0.05 \times 10^4$ CFU/g under compost CS (Table 5).

Table 5. Microbial load (×10⁴ CFU/g) of bell peppers (*Capsicum annuum* L.) as a function of planting density of 50 × 60 cm..

Fertilizer	Fixed application rate	Indicator bacteria for hygiene and spoilage					Pathogenic germs	
		MAB 10^4 UFC/g	Total coliforms 10^4 UFC/g	Thermo Coliforms 10^4 UFC/g	Yeast/Mold 10^4 UFC/g	*E. coli*	Staph 10^4 UFC/g	Salmo
CB	**30 T/ha**	185.75 ± 22.77^{d}	0.77 ± 0.05^{d}	0.50 ± 0.08^{b}	0.72 ± 0.55^{c}	<1	1.46 ± 0.04^{b}	Absent
CBK	**30 T/ha**	376.50 ± 1.00^{c}	3.39 ± 0.90^{b}	0.05 ± 0.01^{d}	1.47 ± 0.24^{a}	<1	2.28 ± 0.08^{ab}	Absent
CS	**30 T/ha**	757.50 ± 43.40^{b}	8.75 ± 0.50^{a}	0.96 ± 0.04^{ab}	0.87 ± 0.05^{b}	<1	3.48 ± 0.05^{a}	Absent
CG	**30 T/ha**	955.00 ± 42.03^{a}	7.50 ± 0.10^{ab}	2.25 ± 0.10^{a}	1.23 ± 0.04^{ab}	<1	1.39 ± 0.08^{d}	Absent
NPK	**30 T/ha**	153.33 ± 8.95^{e}	1.74 ± 0.09^{c}	0.16 ± 0.03^{c}	0.67 ± 0.18^{d}	<1	1.65 ± 0.66^{c}	Absent

Values are expressed as mean ± standard deviation (n = 3). Values followed by different letters within the same column are significantly different at the 5% significance level (ANOVA, $p < 0.05$). Thermo: Thermotolerant; Salomo: Salmonella; Staph: Staphylococcus aureus; MAB: Mesophilic Aerobic Bacteria. *E. coli*: < 1 CFU/g indicates a value below the limit of detection. Salmonella: Abs = not detected in a 25-g sample.

3.4. Microbial Loads (×10⁴ CFU/g) of Sweet Pepper (*Capsicum annuum* L.) Fruits as Affected by Compost Application Rate at a Fixed Planting Density of 50 × 50 cm

3.4.1. Effect of Fertilizer Type on Microbial Loads at a Compost Application Rate of 20 t/ha under a Fixed Planting Density of 50 × 50 cm

At a compost application rate of 20 t/ha and a fixed planting density of 50 × 50 cm, the microbial loads varied among the fertilizer treatments (Table 6).

1) Hygiene and spoilage flora

Aerobic mesophilic bacteria (AMB) showed significant differences among treatments. The highest load was recorded for compost CB, with 922.50 ± 5.10 × 10^4 CFU/g, whereas the lowest value was observed under the NPK treatment

Table 6. Microbial loads (×10⁴ CFU/g) of bell peppers (*Capsicum annuum* L.) fruits according to fertilizer treatment at a compost application rate of 20 t/ha and a fixed planting density of 50 × 50 cm.

Fertilizer	fixed planting density	Indicator bacteria for hygiene and spoilage					Pathogenic germs	
		AMB 10^4 UFC/g	Total coliforms 10^4 UFC/g	Thermo Coliforms 10^4 UFC/g	Yeast/Mold 10^4 UFC/g	*E. coli*	Staph 10^4 UFC/g	Salmo
CBK	**50 × 50**	88.25 ± 1.85^{d}	3.93 ± 0.90^{a}	2.35 ± 0.01^{ab}	0.35 ± 0.10^{e}	< 1	0.18 ± 0.05^{d}	Absent
CG	**50 × 50**	246.00 ± 2.82^{bc}	0.86 ± 0.32^{c}	0.46 ± 0.05^{d}	2.67 ± 0.01^{c}	< 1	1.47 ± 0.10^{b}	Absent
CB	**50 × 50**	922.50 ± 5.10^{a}	3.37 ± 0.11^{b}	1.99 ± 0.12^{c}	3.57 ± 0.18 ^{ab}	< 1	0.18 ± 0.07^{d}	Absent
CS	**50 × 50**	397.50 ± 3.47^{b}	3.13 ± 0.12^{b}	2.47 ± 0.13^{a}	3.80 ± 0.12^{a}	< 1	3.76 ± 0.21^{a}	Absent
NPK	**50 × 50**	78.71 ± 1.99^{e}	0.36 ± 0.65^{d}	0.31 ± 0.06^{e}	1.60 ± 0.14^{d}	< 1	0.93 ± 0.33^{c}	Absent

Values are expressed as mean ± standard deviation (n = 3). Values followed by different letters within the same column are significantly different at the 5% significance level (ANOVA, $p < 0.05$). Thermo: Thermotolerant; Salomo: Salmonella; Staph: Staphylococcus aureus; MAB: Mesophilic Aerobic Bacteria. *E. coli*: < 1 CFU/g indicates a value below the limit of detection. Salmonella: Abs = not detected in a 25-g sample.

(78.71 ± 1.99 × 10^4 CFU/g).

Total coliform loads also differed significantly among treatments (p = 0.01), ranging from 3.93 ± 0.90 × 10^4 CFU/g for compost CBK to 0.36 ± 0.65 × 10^4 CFU/g for the NPK treatment. Thermotolerant coliforms followed a similar pattern, with loads ranging from 2.47 ± 0.13 × 10^4 CFU/g under compost CS to 0.31 ± 0.06 × 10^4 CFU/g under NPK (p = 0.01).

Yeast and mold counts also differed significantly among treatments (p = 0.02). The highest load was observed under compost CS (3.80 ± 0.12 × 10^4 CFU/g), while the lowest was recorded under compost CBK (0.35 ± 0.10 × 10^4 CFU/g).

2) Pathogenic flora

Coagulase-positive staphylococci varied significantly among treatments (p = 0.01). The highest load was recorded under compost CS (3.76 ± 0.21 × 10^4 CFU/g), whereas the lowest values were observed under compost CBK (0.18 ± 0.05 × 10^4 CFU/g) and compost CB (0.18 ± 0.07 × 10^4 CFU/g).

3.4.2. Effect of Fertilizer Type on Microbial Loads at a Compost Application Rate of 40 t/ha under a Fixed Planting Density of 50 × 50 cm

At a compost application rate of 40 t/ha and a fixed planting density of 50 × 50 cm, significant differences were observed among the fertilizer treatments for several microbial groups (Table 7).

1) Hygiene and spoilage flora

Aerobic mesophilic bacteria (AMB) showed significant differences among treatments (p = 0.01). The highest load was recorded under compost CG, with 568.68 ± 31.48 × 10^4 CFU/g, while the lowest value was observed under the NPK treatment (84.31 ± 4.65 × 10^4 CFU/g).

Total coliform loads also varied among treatments, ranging from 5.75 ± 1.33 × 10^4 CFU/g under compost CB to 0.57 ± 0.10 × 10^4 CFU/g under NPK. Thermotolerant coliforms showed a similar variation, with the highest load recorded under compost CG (1.82 ± 0.83 × 10^4 CFU/g) and the lowest under NPK (0.07 ± 0.15 × 10^4 CFU/g).

Yeast and mold counts differed significantly among treatments (p = 0.02), with values ranging from 2.60 ± 1.40 × 10^4 CFU/g under compost CG to 0.67 ± 0.23 × 10^4 CFU/g under NPK.

2) Pathogenic flora

Coagulase-positive staphylococci also varied significantly among treatments (p = 0.01). The highest load was observed under compost CS, with 2.78 ± 0.58 × 10^4 CFU/g, whereas the lowest value was recorded under the NPK treatment (0.50 ± 0.01 × 10^4 CFU/g) (Table 7).

4. Discussion

The use of faecal sludge-derived composts as organic amendments represents a promising strategy for improving soil fertility while promoting the recovery of locally available resources. However, their agricultural application requires prior

Table 7. Microbial loads (×10^4 CFU/g) of bell peppers (*Capsicum annuum* L.) fruits according to fertilizer treatment at a compost application rate of 40 t/ha and a fixed planting density of 50 × 50 cm.

Fertilizer	fixed planting density	Indicator bacteria for hygiene and spoilage					Pathogenic germs	
		AMB 10^4 UFC/g	Total coliforms 10^4 UFC/g	Thermo Coliforms10^4 UFC/g	Yeast/Mold10^4 UFC/g	*E. coli*	Staph 10^4 UFC/g	Salmo
CBK	**50 × 50**	413.56 ± 24.68^b	1.85 ± 0.22^d	1.07 ± 0.60^b	2,08 ± 0.91^{ab}	<1	2.60 ± 0.45^{ab}	Absent
CG	**50 × 50**	568.68 ± 31.48^a	2.82 ± 0.20^c	1.82 ± 0.83^a	2,60 ± 1.40^a	<1	1.95 ± 1.34^d	Absent
CB	**50 × 50**	353.01 ± 29.15^c	5.75 ± 1.33^a	1.07 ± 0.87^b	1,07 ± 0.71^d	<1	2.15 ± 0.84^c	Absent
CS	**50 × 50**	180.25 ± 12.44^d	3.47 ± 0.60^b	0,94 ± 0.85^c	1,54 ± 0.24^c	<1	2.78 ± 0.58^a	Absent
NPK	**50 × 50**	84.31 ± 4.65^e	0.57 ± 0.10^e	0.07 ± 0.15^d	0.67 ± 0.23^e	<1	0.50 ± 0.01^e	Absent

Values are expressed as mean ± standard deviation (n = 3). Values followed by different letters within the same column are significantly different at the 5% significance level (ANOVA, $p < 0.05$). Thermo: Thermotolerant; Salomo: Salmonella; Staph: Staphylococcus aureus; MAB: Mesophilic Aerobic Bacteria. *E. coli*: < 1 CFU/g indicates a value below the limit of detection. Salmonella: Abs = not detected in a 25-g sample.

evaluation of their physicochemical and microbiological quality to ensure both agronomic value and sanitary safety.

After four months of composting, the different composts showed physicochemical characteristics indicative of satisfactory stabilization. The pH values (7.11 - 7.30) reflected near-neutral conditions, commonly associated with advanced compost maturity, while the C/N ratios (16.2 - 20.2) indicated progressive stabilization of organic matter. According to [17], C/N ratios below 20 - 25 are generally considered indicative of mature composts suitable for agricultural use. Moreover, the organic matter contents (22.7% - 29.5%) and the presence of essential nutrients (N, P, K, Ca, and Mg) highlight their potential agronomic value as soil amendments. The differences observed among composts may be related to the origin and initial composition of the faecal sludge, which can influence nutrient availability and final compost quality [18]. Thus, although all composts reached a satisfactory level of stabilization, their intrinsic properties may contribute to differences in their agronomic potential.

From a microbiological perspective, the low levels of hygiene indicator microorganisms, together with the absence of *Salmonella* spp. and the low detection levels of *Escherichia coli* (<1 CFU/g), indicate satisfactory sanitary quality of the composts before field application.

This finding may be attributed to the thermal conditions developed during the thermophilic phase of composting, during which temperatures reached 65˚C - 75˚C. Maintaining elevated temperatures for a sufficient period is considered one of the primary mechanisms responsible for compost sanitization, as it promotes the inactivation of heat-sensitive microorganisms [9] [19].

The high levels of hygiene indicator microorganisms observed under some treatments may be related to the microbiological characteristics of the organic amendments and to the interactions among compost, soil, and plant properties.

Indeed, faecal sludge-derived composts harbor a diverse microbial community involved in organic matter decomposition and nutrient transformation. Several studies have evaluated the effectiveness of thermophilic composting and the influence of the time-temperature conditions established by the U.S. Environmental Protection Agency [20] on the reduction of pathogenic microorganisms during the composting process [21] [22].

During composting, microbial ecological succession progressively takes place. Mesophilic microorganisms dominate the initial stages of organic matter decomposition and are subsequently replaced by thermophilic microorganisms when temperatures exceed approximately 55˚C for several days [21]. This thermophilic phase represents a critical step in the sanitization process because it substantially reduces fecal microorganisms and other heat-sensitive microorganisms [23]. As the compost cools during maturation, it is progressively recolonized by predominantly saprophytic microorganisms involved in organic matter stabilization. Consequently, the presence of aerobic mesophilic bacteria (AMB) in mature compost does not necessarily indicate the persistence of pathogenic microorganisms, but may reflect the activity of microorganisms involved in organic matter decomposition [23].

This microbial succession is consistent with the results obtained in the present study. AMB loads on sweet pepper fruits varied among treatments, with particularly high values recorded under compost CG ($496.67 \pm 3.39 \times 10^4$ CFU/g under certain experimental conditions and up to $955.00 \pm 10.90 \times 10^4$ CFU/g for specific compost application rate-compost combinations). These elevated levels may reflect increased microbial activity resulting from interactions among compost characteristics, the availability of organic substrates in the soil, and environmental conditions favorable for the development of fruit-associated microbial communities.

In contrast, the lower AMB loads observed under compost CS ($57.5 \pm 1.58 \times 10^4$ CFU/g) may be associated with a more advanced degree of compost stabilization or a lower availability of readily degradable organic compounds capable of stimulating microbial activity. Likewise, the relatively low load recorded under the NPK treatment ($80.25 \pm 1.24 \times 10^4$ CFU/g) may be explained by the absence of organic matter inputs, thereby limiting the availability of substrates that support the development of fruit-associated microbial communities.

The observed microbial dynamics are influenced by several factors, including the maximum temperature reached, the duration of the thermophilic phase, aeration, moisture content, the C/N ratio, and the uniformity of turning throughout the composting process [24] [25]. Properly stabilized composts generally exhibit lower levels of indicator microorganisms while maintaining beneficial microbial communities involved in organic matter mineralization and soil biological functioning [26].

In the present study, AMB loads in sweet pepper fruits varied considerably among fertilization treatments. Under the experiment conducted at a fixed compost application rate of 30 t/ha, AMB loads varied according to planting density

and compost type. At 40 × 50 cm, values ranged from 80.25 ± 1.24 × 10^4 CFU/g under NPK to 517.50 ± 5.97 × 10^4 CFU/g under compost CS. At 50 × 50 cm, loads ranged from 57.50 ± 1.58 × 10^4 CFU/g under CS to 496.67 ± 3.39 × 10^4 CFU/g under CG, whereas at 50 × 60 cm, the highest value reached 955.00 ± 10.90 × 10^4 CFU/g under CG. These variations suggest that planting density alone does not fully explain the observed microbial loads. Rather, microbial development on fruit surfaces may result from interactions between compost characteristics, soil conditions, and the microenvironment created by the crop canopy.

The effect of compost application rate was evaluated separately at a fixed planting density of 50 × 50 cm. At 20 t/ha, AMB loads ranged from 78.71 ± 1.99 × 10^4 CFU/g under NPK to 922.50 ± 5.10 × 10^4 CFU/g under compost CB. At 40 t/ha, values ranged from 84.31 ± 4.65 × 10^4 CFU/g under NPK to 568.68 ± 31.48 × 10^4 CFU/g under compost CG. These results show that increasing the compost application rate did not result in a uniform increase in AMB loads across all compost types. This observation suggests that the microbial response was influenced not only by the quantity of compost applied but also by the intrinsic characteristics of each compost.

The observed microbial dynamics may be influenced by several factors, including the maximum temperature reached during composting, the duration of the thermophilic phase, aeration, moisture content, C/N ratio, and the effectiveness of turning throughout the composting process [24] [25]. Properly stabilized composts generally contain reduced levels of fecal indicator microorganisms while maintaining microbial communities involved in organic matter mineralization and soil biological functioning [26].

Total and thermotolerant coliforms also varied among treatments. Under the 20 t/ha treatment at 50 × 50 cm, total coliform loads ranged from 0.36 ± 0.65 × 10^4 CFU/g under NPK to 3.93 ± 0.90 × 10^4 CFU/g under CBK, while thermotolerant coliforms ranged from 0.31 ± 0.06 × 10^4 CFU/g under NPK to 2.47 ± 0.13 × 10^4 CFU/g under CS. At 40 t/ha, total coliform loads ranged from 0.57 ± 0.10 × 10^4 CFU/g under NPK to 5.75 ± 1.33 × 10^4 CFU/g under CB, whereas thermotolerant coliforms ranged from 0.07 ± 0.15 × 10^4 CFU/g under NPK to 1.82 ± 0.83 × 10^4 CFU/g under CG. These variations indicate differences in the microbial conditions associated with the different compost treatments.

The residual presence of coliforms after compost maturation may be explained by several mechanisms, including incomplete reduction during the thermophilic phase, environmental recolonization after maturation, or secondary transfer from soil, irrigation water, or plant surfaces. Several studies have shown that coliform populations decline markedly when thermophilic conditions are maintained for a sufficient period, although recolonization by environmental microorganisms may occur after the sanitization phase.

The fungal flora, represented by yeasts and molds, also varied among treatments. At 20 t/ha, loads ranged from 0.35 ± 0.10 × 10^4 CFU/g under CBK to 3.80 ± 0.12 × 10^4 CFU/g under CS. At 40 t/ha, values ranged from 0.67 ± 0.23

$\times 10^4$ CFU/g under NPK to 2.60 ± 1.40 $\times 10^4$ CFU/g under CG. Yeasts and molds are strongly influenced by microclimatic conditions, particularly surface moisture, the availability of carbon-rich substrates, and the characteristics of the phyllosphere [14] [27]. Sweet pepper fruits may provide favorable conditions for these microorganisms because of their nutrient-rich surfaces and moisture availability. Therefore, the observed variations may result from interactions among compost characteristics, soil properties, and the crop microenvironment [28].

Planting density may also influence the microbial dynamics of fresh produce by modifying air circulation, solar radiation penetration, and the duration of surface wetness. Denser plant canopies can create more humid microclimates that favor microbial persistence, whereas wider spacing may improve air circulation and accelerate tissue drying [29]. However, the present results indicate that the relationship between planting density and microbial loads was not systematic across all compost treatments. This suggests that the effect of density may depend on the interaction between crop microclimate and the characteristics of the organic amendment.

Regarding application rate, increasing the amount of compost applied may modify the availability of organic matter, nutrients, and microorganisms in the soil. However, the effect of application rate depends strongly on the intrinsic quality and maturity of the compost, particularly its microbiological [9] [19]. The results obtained at 20 and 40 t/ha under a fixed density of 50 × 50 cm confirm that the response was not uniform among compost types. Consequently, the application rate should not be considered independently of compost origin and quality when assessing the microbiological quality of crops.

Among the potentially pathogenic microorganisms investigated, coagulase-positive staphylococci showed significant variations among treatments. At 20 t/ha, their loads ranged from 0.18 ± 0.05 $\times 10^4$ CFU/g under CBK and 0.18 ± 0.07 $\times 10^4$ CFU/g under CB to 3.76 ± 0.21 $\times 10^4$ CFU/g under CS. At 40 t/ha, values ranged from 0.50 ± 0.01 $\times 10^4$ CFU/g under NPK to 2.78 ± 0.58 $\times 10^4$ CFU/g under CS. The presence of these microorganisms cannot, however, be directly attributed to compost application, since coagulase-positive staphylococci may originate from human or animal sources and can be transferred to fresh produce during agricultural practices, handling, or environmental exposure [30].

The most important finding from a food safety perspective was the consistent absence of *E. coli* at detectable levels (<1 CFU/g) and the absence of *Salmonella* spp. in all analyzed sweet pepper samples. This result suggests that, under the experimental conditions evaluated, the composting process was effective in limiting the transfer of these major enteric microorganisms to the fruits. However, pathogen survival and transfer in agricultural systems depend not only on the initial microbiological quality of compost but also on post-application environmental conditions, including soil moisture, temperature, solar radiation, and the interval between compost application and harvest [31]. Therefore, appropriate compost-

ing management and good agricultural practices remain essential to maintain the microbiological safety of vegetables produced with faecal sludge-derived composts.

Overall, the results demonstrate that compost type, planting density, and application rate were associated with variations in the levels of several hygiene and spoilage indicators in sweet pepper fruits. However, these variations were not accompanied by detectable contamination by *E. coli* or *Salmonella* spp. under the conditions evaluated. The findings therefore highlight the importance of controlling composting conditions and monitoring the microbiological quality of both organic amendments and harvested vegetables when promoting the agricultural reuse of faecal sludge-derived composts.

5. Conclusions

Considering all the findings, the faecal sludge-derived composts evaluated after four months of composting showed physicochemical characteristics indicative of satisfactory stabilization and potential for agricultural use. Their microbiological characteristics, particularly the absence of Salmonella spp. and the detection of *E. coli* below the detection limit, also indicated effective reduction of the major enteric microorganisms investigated.

The application of the different composts resulted in variations in the microbiological quality of sweet pepper fruits, particularly for aerobic mesophilic bacteria, coliforms, yeasts and molds, and coagulase-positive staphylococci. These variations differed according to compost type, planting density, and application rate, indicating that the microbiological response of the crop was influenced by both the characteristics of the composts and the conditions of cultivation.

However, *E. coli* remained below the detection limit and *Salmonella* spp. was not detected in any of the analyzed fruits, regardless of the fertilization treatment, planting density, or compost application rate. Thus, under the experimental conditions evaluated, the use of properly composted faecal sludge did not result in detectable contamination of sweet pepper fruits by the major enteric pathogens investigated.

Overall, faecal sludge-derived composts may represent a promising organic alternative to exclusive reliance on mineral fertilizers, provided that they undergo adequate composting and are applied under appropriate agricultural practices. Continued monitoring of compost maturity and microbiological quality remains necessary to ensure the safe and sustainable reuse of these organic amendments in vegetable production.

Author Contributions

Bomassaye Roland TAHO: Data collection, investigation, and original draft preparation; Kouakou Ahossi KONAN: Statistical analysis, data validation, manuscript writing and revision; Kra Athanase KOUASSI: Funding acquisition, supervision, and validation of data and results; N'dri Jacob KOUASSI: Tudy direction,

project administration, funding acquisition, supervision, and manuscript writing and revision.

Acknowledgements

The authors sincerely thank all members of the Laboratory for the Improvement of Agricultural Production and the Agro-Valorisation Laboratory at Jean Lorougnon Guédé University for their availability, guidance, advice, and technical support throughout the completion of this work.

The authors also express their deep gratitude to all colleagues, technicians, field workers, and all individuals who, directly or indirectly, contributed to the successful completion of this study. Their support, cooperation, and valuable advice greatly contributed to the achievement of this work.

To all these individuals, the authors extend their deepest appreciation and sincere thanks.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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