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Influence of Rabbit Debris Enriched with Organic Waste on the Agronomic and Sanitary Properties of Compost

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ABSTRACT

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Managing organic waste is an environmental challenge. Composting recycles waste and enhances soil fertility. The effect of adding rabbit debris on compost quality, nutrient recycling, and pathogen reduction is unclear. This study evaluates the impact of various organic wastes, especially with rabbit debris, on nutrient content and microbial load. Composts from different organic wastes, with or without rabbit debris, were monitored over 90 days. Physico-chemical parameters, moisture, temperature, total nitrogen (N), phosphorus (P), potassium (K), and carbon-to-nitrogen ratio (C/N), were measured. Microbiological analyses targeted pathogens such as Clostridium spp., Escherichia coli, Salmonella spp., Staphylococcus spp., Bacillus spp., and yeasts. Multivariate analysis classified compost maturity. Rabbit debris-enriched composts showed a stable thermophilic phase with temperatures up to 65.2 °C and moisture between 35% and 50%. Mixtures BD, CD, and BCD had high nutrient levels, peaking in potassium (4.5 ± 0.2 g/kg in CD), phosphorus (0.176 ± 0 g/kg in BCD), and nitrogen (0.839 ± 0.1 g/kg in B). The C/N ratio ranged from 40.68 ± 3.5 to 18.66 ± 2.1, indicating higher maturity in BCD. E. coli, Clostridium spp., and yeasts decreased significantly, but Salmonella spp. persisted at concerning levels (up to 3.170 log_{10} CFU/g), exceeding NF U 44-051 standards. Composts were grouped as young (D, BC), mature (C, BD, CD), and intermediate (B, BCD). Adding rabbit debris improves thermophilic phase stability and nutrient enrichment but does not fully eliminate pathogens exceeding NF U 44-051 thresholds. Optimizing composting is essential for agricultural sanitary compliance.

Introduction

In the wake of the COVID-19 pandemic, global hunger has increased dramatically. Estimates from the State of Food Security and Nutrition in the World reveal that no fewer than 161 million people will go hungry between 2019 and 2020, bringing the global total to 811 million people facing food insufficiency (FAO SOFI, 2004).

Africa in particular was the most vulnerable continent, with a total of 282 million people suffering from hunger in 2020. With agricultural land limited or even reduced over time, Africa's growing population is a major threat to food security (Bisht and Chauhan, 2020; Mahanty *et al.,* 2017). This demographic growth has a proven influence on food availability in Africa. This impact may be all the more detrimental as Africa's population is set to reach 2 billion by 2050 (UN, 2017). In order to feed this population, farmers are resorting to chemical fertilisers (Nikita and Puneet, 2020).

However, while chemical fertilisers are the main cause of adequate agricultural production for the African population, their excessive use can pose serious problems for current and future generations, such as air, water and soil contamination, land and soil degradation and increased greenhouse gas emissions (Cerda *et al.,* 2018). These synthetic fertilisers are not only harmful to our climate, but also to humans, livestock and microbial life forms (Ahmed *et al.,* 2023). Moreover, for many small farmers in sub-Saharan Africa, the use of fertilisers is expensive and risky, normally costing two to three times more than in other parts of the developing world. In rural areas, the tripling of fertiliser prices since 2020 in a market destabilised by the Ukrainian conflict is forcing farmers to revise their forecasts downwards.

So to increase productivity in these economically weak areas while guaranteeing agricultural biosecurity without any side effects on soil microflora, the environment or human health, it is necessary to look for an alternative to chemical fertilisers for a sustainable agricultural practice that offers economic solutions while combating climate change.

Composting food waste, which is a concern for cities all over the world and particularly in Africa, is a viable solution. Composting is a biological process that transforms organic waste into compost, an organic fertiliser. Compost produced from food waste for agricultural use has received considerable attention, due to its low cost and the possibility of on-site processing (Awasthi *et al.,* 2021), being recently considered as a promising solution for the treatment of organic waste (Zhang *et al.,* 2021).

In Africa, several types of agricultural waste from different production chains have been used as feedstock for composting (Rupani *et al.,* 2023). These include agricultural waste (rice straw, leaf litter, sawdust, banana peel, etc.) (Mtui 2009; Coulibaly *et al.,* (2011); Katakula *et al.,* (2021), solid waste from cellars (Masowa *et al.,* 2020)), and poultry waste (Adetunji *et al.,* 2021).

Among this agricultural waste, cassava and banana peelings, from crops that are staple foods for the rural population, are produced in large quantities in Côte d'Ivoire. Indeed, Côte d'Ivoire is the leading producer of plantain in West Africa, with annual production estimated at over 1,700,000 tonnes (CNRA, 2020).

Average national consumption is estimated at 120 kg per capita per year (CNRA, 2020), for a population of over 29 million. During peeling operations, around 30% of the weight of the fruit is rejected in the form of peelings, representing an annual quantity of around 510,000 tonnes of plantain peelings.

With regard to cassava cultivation, Côte d'Ivoire ranks among the world's leading producers, occupying 12th place with a share of 1.9% of global production, and 7th place at the African level (FAOSTAT, 2017). Between 2005 and 2015, cassava production grew at an average annual rate of 8.5%, from 2.2 to 5.3 million tonnes (Barussaud and Adou, 2019). This expansion has been accompanied by a significant increase in artisanal processing, generating large quantities of peelings.

According to Kouakou *et al.,* (2023), the 46 processing units studied produce around 1,154.95 tonnes of cassava peelings annually. If these figures are extrapolated to the national level, this volume could reach several tens of thousands of tonnes per year, given the large number of small-scale processors operating throughout the country. These plantain and cassava peelings, produced in large quantities and still largely underused, represent a significant source of agricultural waste. However, the majority of this agricultural waste is abandoned to landfill or burnt, contributing to environmental pollution. In addition, their decomposition in landfill, releases methane, a greenhouse gas 28 times more potent than CO_2, exacerbating climate change (Everitt *et al.,* 2020).

To reduce the negative impact of these cassava and plantain by-products on the environment, various recovery methods (use of peelings in animal feed, biogas production, mushroom production, activated carbon production, etc.) and treatment methods (compost (1% to 6%), anaerobic digestion (<0.6%), incineration and landfill (>90%) have been developed.) and treatment methods (compost (1% to 6%), anaerobic digestion (< 0.6%), incineration and landfill (> 90%)) have been implemented by some authors (Odediran and Ojebiyi, 2017; Kouadio *et al.,* 2020 Cruz *et al.,* 2021; Kayiwa *et al.,* 2021; Thi *et al.,* 2015; Puspitaloka *et al.,* 2022). Despite this diversity of recovery routes and processing methods for cassava and banana peelings, their use for composting remains largely unexplored in Côte d'Ivoire.

More efficient management of this agricultural waste, particularly through composting, is a promising alternative for meeting the agricultural and environmental challenges facing Côte d'Ivoire. By transforming these peelings into compost, it is possible to reduce their accumulation in landfill sites, limit methane emissions and sustainably enrich the soil. This practice also reduces dependence on chemical fertilisers, which are often expensive and harmful to the soil and the environment in the long term.

However, they are rarely recycled, and more often than not end up in landfill sites or are burnt, contributing to environmental pollution. Moreover, when this food waste decomposes in landfill, it releases methane, which is 28 times more potent than CO in contributing to climate change (Everitt *et al.,* 2020). In an attempt to reduce the negative impact of these cassava and plantain by-products on the environment, recovery methods (use of peelings in animal feed, biogas production, mushroom production, activated carbon production, etc.) and treatment methods (compost (1% to 6%), anaerobic digestion (< 0.6%), incineration and landfill (> 90%)) have been implemented by some authors (Odediran and Ojebiyi, 2017; Kouadio *et al.,*2020; Cruz *et al.,* 2021; Kayiwa *et al.,* 2021; Thi *et al.,* 2015; Puspitaloka *et al.,* 2022).

Despite this diversity of recovery routes and processing methods for cassava and banana peelings, their use for composting remains largely unexplored in Côte d'Ivoire. Composting manioc and banana peelings therefore appears to be a promising alternative for meeting the agricultural and environmental challenges facing Côte d'Ivoire. By transforming these peelings into compost, it is possible to reduce their accumulation in landfill sites, limit methane emissions and enrich the soil in a sustainable way. This practice also reduces dependence on chemical fertilisers, which are often costly and harmful to the soil and the environment in the long term.

This waste is often combined with animal excrement to optimise the composting process (Awasthi *et al.,* 2020).

Some existing studies have mainly verified the feasibility of composting rabbit manure with other agricultural wastes (Islas-Valdez *et al.,* 2015; Cholis and Nursita, 2022; Li *et al.,* 2022).

However, various zoonotic pathogens present in animal excrement-based composts in particular have been reported by several authors. Manures from cattle, pigs, sheep, goats and poultry are sometimes used as composts for growing fruit and vegetables, but they are also known to carry many food-borne pathogens (Harris *et al.,* 2013; Black *et al.,* 2021). Some bacteria present in manure, such as E. coli and Salmonella, have often been implicated directly or indirectly in human disease outbreaks (Bicudo and Goyal, 2003; Guan and Holley, 2003; Hutchison *et al.,* 2004).

In addition, several pathogens have been described as responsible for enteric diseases in rabbits. Among these, enteropathogenic strains of *Escherichia coli* (EPEC) play a central role in the aetiology of these disorders (Boullier *et al.,* 2006; Licois *et al.,* 2009). Other bacteria are also responsible for enteric pathologies in rabbits. These include *Clostridium spiroforme*, which produces a binary toxin similar to the iota toxin of *Clostridium perfringens*. This toxin is considered to be the main virulence factor in rabbit enterotoxaemia. Clostridium spiroforme is generally detected in the advanced stages of digestive disorders and its appearance has often been associated with dysbiosis following antibiotic treatment (Carman and Borriello, 1984; Licois *et al.,* 2009). Salmonellosis is another important bacterial infection, manifesting as metritis in adult rabbits and septicaemia in young rabbits, while also inducing digestive signs in growing animals (Agnoletti *et al.,* 1998; Aboelhadid *et al.,* 2021).

In addition to bacteria, parasites, and in particular coccidian protozoa, play a crucial role in enteric diseases. At least eleven species of Eimeria have been identified in rabbits, and the severity of infection depends on the species involved and the intensity of infestation (Licois *et al.,* 2009). Finally, other pathogens, whose impact is often amplified by various risk factors such as medical treatment, inadequate feeding or unfavourable climatic conditions, can also induce enteric disorders. These include group A rotavirus (Lavazza *et al.,* 2019), *Clostridium perfringens* (Garcia *et al.,* 2014), Enterococcus hirae (Vela *et al.,* 2010) and enterotoxigenic Bacteroides fragilis (Malo *et al.,* 2019).

Some of these pathogenic micro-organisms, when they contaminate compost applied to agricultural land, can infect humans who consume fresh produce. This is the case even when the pathogens are only present at very low concentrations, as only 10 cells of some pathogens are needed to cause human infection (Alegbeleye *et al.,* 2018). An in-depth study by Sobsey *et al.,* (2006) clearly established a link between the spreading of animal manure on land and the potential contamination of products. The spreading of raw or poorly treated animal waste can introduce human pathogens into cultivated land (Heinonen-Tanski *et al.,* 2006).

These observations indicate that organic compost supplemented with rabbit droppings may constitute a potential refuge for food-borne pathogens. Spreading composts made from organic waste and animal excrement on agricultural land without controlling their microbiological quality is a potential route by which pathogens can enter the human food chain (Brochier *et al.,* 2012). A safe and functional application of this organic waste supplemented with rabbit detritus in agriculture therefore requires in-depth knowledge of its physico-chemical composition and microbiological quality, so that possible impacts on the soil and plants can be determined according to its stability and maturity, among other variables.

In view of the above, it is necessary to: (i) analyse the physicochemical parameters of the produced compost, such as pH, moisture content, and nutrient levels; (ii) assess its microbiological quality by detecting potential pathogenic microorganisms.

This approach will help to better understand the impact of this innovative combination on the quality of the compost and its effectiveness as an organic fertiliser. By valorising these agricultural wastes, the study thus contributes to the sustainable management of biowaste while offering an alternative to chemical fertilisers for improving soil fertility in Côte d'Ivoire. The focus will be on the microbiological safety of the compost to ensure its safe use in agriculture. The results obtained could serve as a reference for optimising compost production in Côte d'Ivoire and promoting sustainable agriculture.

Materials and Methods

Choice of waste

Côte d'Ivoire, as the largest banana producer in West Africa and one of the world's leading cassava producers, plays a major role in the production of these crops. Bananas and manioc, which are widely grown and consumed in the country, generate large volumes of organic waste, particularly peelings. These agricultural residues, which are often under-utilised, offer an opportunity for sustainable recovery through composting, enabling the production of a natural fertiliser. This approach is part of a circular economy, transforming waste into agronomic resources, reducing pollution and promoting more sustainable agriculture.

Waste preparation and composting

Food waste was composted at the agricultural research farm of NANGUI ABROGOUA University, Côte d'Ivoire (5° 23‘ 19’ N; 4° 0‘ 54’ W) for 90 days (from 13 October 2022 to 08 January 2023), according to the method described by Gnimassoun *et al.,* (2020) using rabbit detritus as a bulking agent. The food waste used was banana peelings and cassava peelings from two restaurants collected in the commune of Yopougon in Abidjan.

The rabbit waste came from a domestic breeding farm in the commune of Yopougon in Abidjan. The waste was collected in 100 kg sterile plastic fibre bags and transported to the farm for composting. Before composting, banana and manioc peelings were carefully cut into small pieces using a cutlass to speed up the degradation process.

Seven types of compost were formulated for this study (Table 1): (1) compost consisting solely of 60 kg of rabbit detritus (D), (2) compost consisting solely of 60 kg of banana peelings (B), (3) compost consisting solely of 60 kg of cassava peelings (C), (4) compost consisting of 30 kg of rabbit detritus + 30 kg of banana peelings (DB), (5) compost consisting of 30 kg of rabbit waste + 30 kg of cassava peelings (DC), (6) compost consisting of 30 kg of banana peelings + 30 kg of cassava peelings (BC) and (7) compost consisting of 20 kg of banana peelings +

20 kg of cassava peelings + 20 kg of rabbit detritus (BCD) in seven different compost bins of dimensions 1 m×1 m × 0.15 m. Once the different mixes had been prepared, the composts were watered in small quantities using a 15 litre watering can and turned over regularly twice a week for three weeks, in order to promote aeration and improve the biological degradation of the waste.

Monitoring of some physico-chemical parameters of organic matter during composting

Parameters such as pH, moisture content and temperature were monitored during composting. These parameters were determined at 0, 10, 20, 30, 40, 50, 60, 70, 80 and 90 days of composting. The pH was determined on samples of aqueous compost suspensions taken from the seven heaps using the method described by Yu *et al.,* (2009), with a few modifications. For the measurement, a quantity of 20g of compost from each heap corresponding to the different analysis times was homogenised in 100 ml of sterile distilled water and the reading was taken using a Hanna-type pH meter (Hanna instrument, France). Moisture content was assessed using the AFNOR NF U 44-171 (1996) drying method as described by Yobouet *et al.,* (2010) with a few modifications. For each sample, a mass of 100.0 ± 0.1 g was taken and placed into a laboratory moisture meter (model KERN MLS 50-3), set at a temperature of 105 ± 2 °C. Drying was maintained for approximately 24 hours, or until the mass stabilized (constant weight). The moisture content was directly determined from the digital dial of the device.

Furthermore, the temperature of each pile was measured in situ using a precision digital thermometer (model HANNA HI 98509 Checktemp®, accuracy ±0.1 °C).

Determination of the element content (C, N, P and K) of waste used for composting and mature composts

The element content (C, N, P and K) was determined using an atomic adsorption spectrophotometer with an air-acetylene flame (Varian AA 20, Syndney Australia) after mineralisation and mixing of 0.5 g of dried and ground sample taken from each pile of waste used for composting (D0) and mature composts (D90) in a mixture (1:12 w/v) of concentrated nitric acid and hydrochloric acid (3:2 v/v).

Assessing the level of potentially pathogenic micro-organisms in compost

The most common criteria used to assess the microbial quality of compost are faecal indicator bacteria and Salmonella with reference to the presence of pathogens. In the present study, samples of mature compost from used waste were analysed for microbial parameters including *Echerichia coli*, *Clostridium perfringens* as indicator microorganisms and Salmonella and *Staphylococcus aureus* as potentially pathogenic microorganisms. To assess the microbiological quality of the compost, the microbial count was carried out by adding 10 g of each compost collected during the various analysis times (at 1, 10, 20, 30, 40, 50, 60, 70, 80 and 90 days of composting) to 90 ml of sterile buffered peptone water (AES Laboratoire, COMBOURG France) in 250 ml Erlenmeyer flasks. The solution was mechanically mixed at 150 rpm for 30 min at 25°C. Finally, the suspensions of each type of compost were serially diluted and used for microbial counts on seven appropriate culture media. Eosin and Methylene Blue agar (EMB) poured into Petri dishes and incubated at 37°C for 24 hours was used as the medium for counting *Escherichia coli*.) Yeasts and moulds were counted and isolated using Sabouraud Chloramphenicol agar (Bio-Rad, France) poured into Petri dishes and incubated at 30°C for 48 to 72 hours. A selective agar for Bacillus cereus (Condalab, Madrid, Spain) was used to enumerate the vegetative forms of *Bacillus cereus* in the various mature compost samples. The presumptive genera of *Clostridium perfringens* were counted on tryptone sulphite neomycin agar (TSN). CHROM agar Staph aureus (CSAM) (CHROMagar Microbiology, Paris, France) was used to enumerate the presumptive germs of *Staphylococcus aureus*. It was poured into Petri dishes and incubated at 37°C for. 24 h. For Salmonella enumeration, CHROMagar™ Salmonella agar (CHROMagar Company, Paris, France) poured into Petri dishes and incubated at 37°C for 24 h was used.

Statistical analysis

Statistical tests were carried out using XLSTAT software, version 2016. One-way analyses of variance (ANOVA) and Duncan's tests were used to compare the physico-chemical characteristics (pH, moisture, temperature) and nutrient content of each compost formulation. Differences were considered significant for values of $P < 0.05$. A Principal Component Analysis

(PCA) followed by a Hierarchical Ascending Classification (HAC) was carried out using R 3.1.3 software to classify the composts produced on the basis of their similarities. For the HAC, Ward's criterion was used, with 80% homology. This analysis and classification was completed by a biplot to classify composts according to their stage of degradation, their microbiological safety and their potential for agricultural applications. These tools offer an effective way of understanding composting processes, optimising compost management and guaranteeing its quality for agriculture.

Results and Discussion

Variations in pH, humidity and temperature during the composting process

Safe and effective use of composts produced from organic waste enriched with rabbit detritus in agriculture requires in-depth analysis of their physico-chemical composition as well as the load of potentially pathogenic micro-organisms involved in the composting process.

This study analyses composts produced from organic waste generated by restaurants in Yopougon, Côte d'Ivoire, enriched with rabbit detritus from a farm in the municipality. The composts were produced on the campus of Nangui Abrogoua University over a period of 90 days. Physico-chemical and microbiological analyses were carried out on the six piles of composted waste in order to assess the impact of the addition of rabbit detritus on the thermal dynamics, nutrient content (N, P and K) and microbiological quality of the composts.

Variations in pH, moisture content and temperature during the composting process showed irregular changes from one compost to another, as illustrated in Figures 1-3.

The initial pH of all the waste used for composting was low, ranging from 5.8 to 6.8 and this pH increased between days 10 and 40 of the composting process to reach values between 6.65 and 7.4 as shown in Figure 1.

The pH value of all the composts between days 10 and 40 was acidic (5.6-6.8) due to the release of organic acids from the waste used for composting (Oviedo Ocaña *et al.,* 2019). This pH gradually changed from an acidic state to a neutral range before becoming acidic again on the 90 th day of composting due to ammonia releases, the complete mineralisation of intermediate metabolites and the conversion of organic acid into CO_2 by microbial activity (Huang *et al.,* 2004; Iqbal *et al.,* 2015; Oviedo-Ocaña *et al.,* 2019). At the end of the composting process, the pH of all the composts analysed was in the range of 6.2 to 7.4, characteristic of mature compost, as previously reported by Bustamante *et al.,* (2008); Moubareck *et al.,* (2023). According to these authors, conventional composting requires a pH value of between 6 and 8 to break down the biomass optimally, and our composts were reported with pH values within this range.

Moisture content, a key factor influencing compost quality, was monitored throughout the composting process. It plays an essential role by having a direct impact on microbial activity and the decomposition of organic matter. Regular moisture monitoring is essential to optimise the quality of the final compost and prevent the inconvenience caused by incomplete degradation. Unlike pH, the moisture content of composts decreased throughout the composting process, as shown in Figure 2.

At the start of the process, all the agricultural waste analysed had a higher initial moisture content (44 to 58%), within the standard range of 55 to 70% required for composting food waste (Yeh *et al.,* 2020; Aj Khatib *et al.,* 2023). During the composting process, all composts showed a significant decrease in moisture, with notable differences in the rate of this decrease, depending on the composition of the waste. Compost 'D'and 'BD' showed a marked decrease in moisture, particularly from day 30. The initial moisture content (D0) of compost 'D'was 44%, and decreased steadily throughout the process, reaching 23% at D90. The decrease was gradual, but less marked at first, with values remaining around 38% until D20, before starting to fall more rapidly. The 'BD' compost starts with a higher moisture content (58%) and undergoes a more marked reduction from the outset, reaching 28.12% at D90. The reduction is more rapid in this compost, particularly after D40. These composts have relatively low final moisture contents, suggesting efficient degradation of organic matter.

With a moisture content of 30% at D90, compost 'B' loses its moisture more slowly than the other composts. This could be due to organic matter that is more resistant to degradation or to higher moisture retention, as suggested by Dolly *et al.,* (2020). Composts 'C'and 'BC' also lose their moisture regularly, but the reduction is less rapid than in composts 'BD' and 'D'. They show a tendency to stabilise before reducing their moisture further after D60. The 'CD' and 'BCD' composts followed a similar trend, with a steady decrease in moisture, but with slightly less pronounced drops compared to the 'BD' and 'D'composts. The 'CD' compost starts with 51% moisture and shows a steady decline, reaching 22.75% at D90. The decrease is fairly linear until D40, when it stabilises before starting to fall again after D60.

The 'BCD' compost loses moisture steadily, although to a slightly lesser extent than the 'BD' compost. The 'CD' and 'BCD' composts show a marked decrease in moisture, particularly from day 30, and have relatively low final moisture contents, suggesting efficient degradation of the organic matter. In general, composts based on materials such as banana and cassava peelings ('C'and 'BC') lose their moisture more slowly, which could be linked to the higher water retention in these materials.

At the end of the process, the moisture content of all composts decreases progressively to reach values of between 22.75 and 30%, outside the standard range of 40-50% moisture content recommended by the US composting council for mature composts. According to the authors of this instruction manual, composts that are too dry (35% moisture content or less) can be dusty and irritating to work with, while composts that are very wet (55-60%) can become heavy and lumpy, making them more difficult to apply and more expensive to deliver.

However, some studies have reported different optimum moisture levels for successful composting. Liang *et al.,* (2003) recommended a moisture content of 50% as the minimum requirement for adequate microbial activity. Ahn *et al.,* (2008) suggested that the optimum moisture content of a highly stabilised soil compost mixture is around 25% (wet basis). In addition, composting standards set by the US Environmental Protection Agency (EPA) and some European standards recommend a moisture content of 30-40% for products marketed as stabilised compost, ensuring that the product is well matured and free from risks to soils. This wide range of optimum moisture contents reported by these studies means that there is no generally applicable optimum moisture level for various composting materials. Since the optimum moisture content depends largely on the physical, chemical and biological characteristics of the raw material, the optimum moisture content must be determined for a specific target material. This is because each material has unique physical, chemical and biological characteristics, which affect the relationship between moisture content and its corollary factors, water availability, particle size, porosity and permeability. The changes in temperature during composting are illustrated in Figure 3. At the start of composting (D0), all the compost heaps recorded temperatures ranging from 28±0.42 to 31±0.72°C, slightly lower than the ambient temperature determined, which was 34°C.

During the composting period, the composts passed through four temperature phases: the mesophilic phase lasting 10 days (D0-D10), with temperatures ranging from 28±0.34 to 38.1±0.43; the thermophilic phase (D20-D40), with temperatures ranging from 41.1±0.48 to 62±0.73°C, lasting 20 days; the cooling and stabilisation phase (D50-D60) when temperatures oscillated between 47.25±0.43 and 58.4±1.3°C and the maturation phase (D50-D90) when temperatures fell from 50.5±0.05 to 29±0.38°C.This change in temperature in compost heaps is closely linked to microbial activity and is normally considered to be one of the main parameters used to monitor composting efficiency and compost quality (Bustamante *et al.,* 2008).

Compost 'D'shows a relatively rapid rise in temperature, reaching a peak of 62°C, followed by a gradual decrease to 32°C at D90. This suggests that the organic matter in this compost was degraded relatively quickly at first, but that degradation slowed down thereafter. Compost 'B' showed a slower rise in temperature (peak at 57°C) and a drop to 31°C at D90. This may indicate that the organic matter in this compost is degraded more slowly or that the composition of the compost is less conducive to rapid degradation.

Compost 'B' showed a slower rise in temperature, peaking at 57°C before dropping back to 31°C on day 90. This drop in temperature, from 57°C to 31°C, can be interpreted as an indicator of a slowdown in the biological degradation process. Since composting is an exothermic process, the temperature is generated mainly by microbial activity, particularly that of the thermophilic bacteria that degrade the organic matter (Finore *et al.,* 2023). However, after an initial phase of rapid degradation, thermophilic micro-organisms, which require high temperatures, diminish in number and are gradually replaced by mesophilic micro-organisms, which operate at more moderate temperatures (Liu *et al.,* 2022; He *et al.,* 2022). This natural transition within the microbial community leads to a reduction in heat production (Rastogi *et al.,* 2020), thus contributing to the drop in temperature recorded, as in the case of compost

'B'. Another possible explanation for this drop in temperature could be linked to depletion of the easily degradable substrate as composting progresses (Franke-Whittle *et al.,* 2014). Initially, simple organic materials, such as sugars and proteins, are rapidly degraded, generating high heat production (Shiyang *et al.,* 2021). However, as these substances are consumed, more complex materials, such as lignins, remain, degrading more slowly and generating less heat. This change in compost composition could therefore explain the drop in temperature, as observed in compost "B".

Compost 'C'also reached a fairly high temperature peak at 59°C, then dropped to 30°C at D90, similar to compost 'D'. It shows a similar composting dynamic, but is slightly more stable in its thermophilic phase. Simple composts such as 'D'and 'B' show similar temperature peaks but cool down more quickly, suggesting a rapid depletion of degradable organic matter or a faster but less uniform process.

On the other hand, the combined composts, such as 'BD', 'CD', 'BC' and 'BCD' containing rabbit detritus, show composting dynamics where temperatures remain relatively higher or more stable for longer compared to single composts. For example, the 'BCD' compost maintains relatively stable temperatures until D60 (around 51°C), which could mean more uniform degradation or better management of the organic matter thanks to the combination of wastes. At D90, it still remained at 29°C, suggesting that degradation was not completely complete but had reached a more advanced stage than the other composts. These observations suggest that the use of diversified wastes (such as 'BCD') could improve composting efficiency by maintaining more uniform and prolonged degradation. Similar results were observed by Abderrahim *et al.,* (2024) when composting four waste mixtures [horse manure + green waste (M1), olive grove + green waste (M2), sewage sludge + phosphogypsum + green waste (M3) and green waste (M4)] in Marrakech, Morocco.

Furthermore, combined composts such as 'BD', 'CD', 'BC' and 'BCD', incorporating rabbit detritus, show composting dynamics characterised by higher and more stable temperatures over a prolonged period compared with simple composts. This thermal stability could be explained by the intense activity of the bacteria present in rabbit droppings, which play a key role in the biodegradation of organic matter. In particular, thermophilic and mesophilic micro-organisms promote a rapid rise in temperature and the maintenance of a prolonged thermophilic phase, which is essential for efficient decomposition and the elimination of pathogens. What's more, the high nitrogen content of rabbit droppings helps to stimulate microbial activity by providing a source of rapidly assimilable nutrients, which speeds up the composting process and promotes a more homogenous breakdown of organic matter.

As an example, the "BCD" compost maintains relatively stable temperatures up to day 60 (around 51°C), suggesting more uniform degradation or better organic matter management due to the combination of waste materials. By day 90, it still records a temperature of 29°C, indicating that degradation is not yet fully complete but has reached a more advanced stage compared to other composts. These results suggest that incorporating diverse waste materials, as in the "BCD" compost, could improve composting efficiency by ensuring more uniform and prolonged degradation. Similar observations were reported by Abderrahim *et al.,* (2024) during the composting of four waste mixtures in Marrakech, Morocco: horse manure + green waste (M1), olive grove waste + green waste (M2), sewage sludge + phosphogypsum + green waste (M3), and green waste alone (M4). These studies confirm the positive impact of combining various substrates on thermal stability and the efficiency of the composting process.

In general, most of the composts reached temperatures above 55°C between D20 and D50, followed by a gradual drop to temperatures close to those of the ambient temeperature, indicating the transition to the maturation phase. For example, compost D exceeded 55°C between days D20 and D40, peaking at 62°C at D40. Compost B reached a temperature of 55°C between D30 and D40, with a peak of 57°C at D40. Compost C exceeded 55°C between D30 and D50, reaching 59°C at D50. This thermophilic phase is crucial for the efficient decomposition of complex materials such as lignin and polysaccharides, as well as for killing pathogens and weed seeds (Wan *et al.,* 2020). According to Zhang *et al.,* (2013), this temperature range of 55 to 60 °C for more than 3 days is essential during the composting process to obtain pathogen-free compost. However, differences in thermal profiles between composts can be attributed to the composition of the waste used, the amount of oxygen available, humidity and other environmental factors that influence microbial activity (Maria *et al.,* 2016: Lin *et al.,* 2022).

Nutrient content of raw waste and mature composts

The types of waste used to formulate the different composts have varying nutrient (NPK) compositions as shown in Table 2a, and the choice of waste for composting will depend on the specific nutrient requirements of the soil or crops to be fertilised.

For example, type 'D'waste has a high phosphorus content (0.810 g/kg) but a low potassium content (2.688 g/kg), which could make it a good complement to waste with a higher potassium concentration for nutrient balance. As for type 'B' waste, although phosphorus is relatively low (0.207±0.1), potassium (8.419 ±0.2) is much higher, which could be beneficial for crops requiring more potassium. Type 'M'waste has a slightly higher C/N ratio (35.14±0.9) and a relatively low potassium content (1.924±0.2), which may limit its effectiveness as a nutrient-rich compost material in the short term.

On the other hand, the combined waste types ('BD', 'MD', 'BM' and 'BMD') containing rabbit detritus appear to have a good nutrient balance, with moderate nitrogen and phosphorus content, but high potassium concentration. This could indicate that these wastes are particularly beneficial for soils requiring a high potassium supply. The 'BMD' type, in particular, is the richest in all NPK elements, suggesting that it may be the most complete for effective composting.

However, analysis of the data concerning the NPK (Nitrogen, Phosphorus, Potassium) composition of mature composts shows a decrease in the total contents of N, P and K during the composting process and a wide variation according to the type of compost, as shown in Table 2b. The data provided in tables 2b and 3b respectively on the NPK (Nitrogen, Phosphorus, Potassium) content and the C/N ratio of mature composts make it possible to compare the different nutritional qualities of composts and their ability to meet plant needs according to their chemical and biological characteristics.

The choice of compost should therefore be guided by the specific needs in terms of speed of degradation and type of nutrients (N, P, K) required by the target plants or soil.

From the above, type 'D'compost (C: 23.36 % ± 0.6; N: 0.24 % ± 0.1; P: 0.130 % ± 0.03; K: 0.45 % ± 0.1 and C/N: 97,33 ± 4) with a high C/N ratio and low N, P and K content, is suitable for long-term applications where a slow and gradual supply of nutrients is desired, such as for perennial plants or in agricultural systems with rich soils.

With the following characteristics: (C: 17.291 % ± 0.2; N: 0.839 % ± 0.1; P: 0.171 % ± 0.03; K: 2.8 % ± 0.3 and C/N: 20,61 ± 1,7); type 'B' compost is the most balanced compost for short-term applications with a low C/N ratio and high concentrations of N, P and K.

It has the lowest C/N ratio of all the composts, which suggests that it is well decomposed and that nutrients are available more quickly. Its highest phosphorus content of all composts makes it a good choice for crops requiring a significant phosphorus supply, such as root vegetables or flower crops. This high phosphorus content, combined with a high nitrogen and potassium content, makes Compost 'B' a well-balanced compost for crops with high nutrient requirements.

Type 'C'compost (C: 16.850 % ± 0.4; N: 0.22 % ± 0.1; P: 0.084 % ± 0.0; K: 0.924 % ± 0.2 and C/N: 76.59 ± 5.2) has a low nitrogen content (0.22 %) and an even lower phosphorus content (0. 084%), which could make it more suitable for plants that do not require a high input of these elements, or for crops that are not very demanding in terms of nitrogen. Potassium levels are also relatively low compared with other composts.

The 'BD' compost (C: 25.22 % ± 0.4; N: 0.62 % ± 0.1; P: 0.11 % ± 0.1; K0: 92 % ± 0.1and C/N: 40.68± 3,5) differs from the other composts in that it has a very high nitrogen content (0.839 %), which can be advantageous for plants in terms of vegetative growth. On the other hand, its potassium content is very high (2.8 %), which suggests a rich compost to encourage flowering and fruiting in plants. The phosphorus content is moderate. This compost is well suited to market garden crops with low or moderate nitrogen and potassium requirements, such as root vegetables, leafy vegetables or cereals with low nutrient requirements.

The 'CD' type compost (C: 24.4 % ± 0.3; N: 0.82 % ± 0.2; P: 0.09 % ± 0.0; K: 4.5 % ± 0.2 and C/N: 29.76 ± 3,6) has a high potassium content (4.5 %), which could make it particularly suitable for fruit crops or vegetables with a high potassium requirement.

However, it may not be suitable for crops that need more phosphorus, such as root vegetables or certain flowering plants. The nitrogen content is also fairly high (0.82%), making it a good compost for stimulating growth.

'BMD' compost (C: 10.615 % ± 0.4; N: 0.569 % ± 0.3; P: 0.176 % ± 0.1; K: 1.83 % ± 0.4 and C/N: 18.66 ± 2,1) has moderate values in terms of carbon, nitrogen, phosphorus and potassium, making it relatively balanced and adaptable to a wide range of crops. Its nitrogen content (0.569%) is sufficient to support growth, but without excess.

As mentioned earlier, all the composts used in this study had low nitrogen and phosphorus availability. According to Moubareck *et al.,* (2023), this low availability of nitrogen and phosphorus in crushed composts can be strongly linked to the immaturity of the compost. And one of the causes of compost immaturity could be low water content, an important factor for the growth of microbial decomposers (Moubareck *et al.,* 2023). The nitrogen levels determined in the mature composts, with percentages ranging from 0.02 to 0.15%, were below the standard range of 0.5 to 2.5% established by the US Composting Council in mature composts. The standard range for nitrogen is between 0.5 and 2.5%, and most of our samples fell outside this range. Only composts of types 'B' (0.839±0.1%), 'BD' (0.62 ± 0.1%), 'MD' (0.82 ± 0.2%) and 'BMD' (0.569±0.3%) were within the standard range established for nitrogen, the other composts had a nitrogen concentration of less than 0.5%.

Several factors may explain the low nitrogen content of these composts: microbial assimilation, where nitrogenophilic micro-organisms use nitrogen for their growth, reducing its availability in the compost; nitrate leaching, particularly in the presence of excessive humidity, which leads to its loss in percolating water; and ammonia volatilisation, favoured by an alkaline pH (Maeda *et al.,* 2011). In addition, the nature of the raw materials, which are often low in nitrogen, has a direct influence on the final nitrogen content of the compost, as in the case of cassava and banana peelings [(banana peelings: 1,763 ±0.2%); (cassava peelings: 1,612 ±0.1%)] (Maeda *et al.,* 2011). According to Han *et al.,* (2025). The most common method for improving nitrogen recovery rates is to optimise composting process parameters and microbial population structures. For example, Liu *et al.,* (2023) adjusted the carbon-nitrogen-phosphorus-sulphur ratio in cow manure compost to regulate microbial nutrient mineralisation and improve nitrogen utilisation.

Furthermore, the nitrogen (N) contents of the composts concocted in this study were low compared to those reported by Moharana and Biswas (2016) for chickpea cane (1.63%) < rice straw (1.51%) < mustard cane (1.50%) < wheat straw (1.32%)< tree leaves (1.21%) composts after 120 days of composting period and Kadir *et al.,* (2016) for food waste compost from Makanan Ringan Mas in Malaysia after four weeks of composting. However, Comparé *et al.,* (2010) observed different values with a rate of 0.36% nitrogen for public landfill waste.

These variations are mainly due to differences in the initial composition of the substrates, with some materials (protein-rich agricultural waste, legume residues) naturally containing more nitrogen than protein-poor substrates (straw, wood, crop residues).

Table.1 Formulation of compost types according to the waste used (rabbit detritus, banana peelings, cassava peelings)

Type of compost	D	B	C	Description
D	1	0	0	100% rabbit detritus (1:0:0)
B	0	1	0	100% banana peelings (0:1:0)
C	0	0	1	100% cassava peelings (0:0:1)
DB	1	1	0	50% D + 50% B (1:1:0)
DC	1	0	1	50% D + 50% C (1:0:1)
BC	0	1	1	50% B + 50% C (0:1:1)
BCD	1	1	1	33,3% D + 33,3% B + 33,3% (1:1:1)

In the table, the values 1 and 0 represent the presence or absence of waste in each type of compost.

Table.2a Nutrient content of raw waste used for composting

Types of waste	C	N	P	K
D	50.106±0.4[b]	1.667± 0.3[b]	0.810 ± 0.02[a]	2.688± 0.1[c]
B	49.984±0.3[b]	1.763±0.2[b]	0.207± 0.0[b]	8.419 ±0.7[b]
C	56.650±1.2[a]	1.612±0.1[a]	0.184± 0.0[b]	1.924±0.03[d]
BD	54.12±0.5[a]	1.560.4[b]	0.2± 0.01[b]	9.2± 0.4[b]
CD	52.4±1.3[ab]	1.8± 0.2[ab]	0.23± 0.02[b]	10.25±0.3[a]
BC	55.7± 1.4[a]	2.1±0.1[a]	0.198± 0.0[b]	10.2± 0.7[a]
BCD	53.6± 0.8[ab]	2.4± 0.5[a]	0.27± 0.01[b]	11.34± 0.8[a]

The values given are the mean ± standard deviation (SD) of three measurements. In the same column and for each compost, mean values bearing the same letter are not significantly different at the 5% threshold ($p < 0.05$).

Table.2b Nutrient content of mature composts

Types of compost	C	N	P	K
D	23.36±0.6[a]	0.24±0.1[c]	0.130±0.03[a]	0.45±0.1[d]
B	17.291±0.2[b]	0.839±0.1[a]	0.171±0.03[a]	2.8±0.3[b]
C	16.850±0.4[b]	0.22±0.1[c]	0.084± 0.0[c]	0.924±0.2[c]
BD	25.22±0.4[a]	0.62 ± 0.1[ab]	0.11± 0.1b	0.92±0.1[c]
CD	24.4±0.3[a]	0.82 ± 0.2[a]	0.09± 0[c]	4.5± 0.2[a]
BC	5.072±0.5[d]	0.327±0.2[c]	0.160±0.04[b]	1.8±0.5[c]
BCD	10.615±0.4[c]	0.569±0.3[b]	0.176±0[a]	1.83±0.4[c]

The values given are the mean ± standard deviation (SD) of three measurements. In the same column and for each compost, mean values bearing the same letter are not significantly different at the 5% threshold ($p < 0.05$).

Table.3a The C/N ratio of raw waste used for composting

Types of compost	Ratio C/N
D	30.06 ± 1.8[b]
B	28.35±1.9[b]
C	35.14 ± 0.9[a]
BD	34.69± 1.2[a]
CD	29.11±1.1[b]
BC	26.52 ± 0.6[c]
BCD	22.33 ± 0.3[d]

Fig.1 pH variation during the composting period

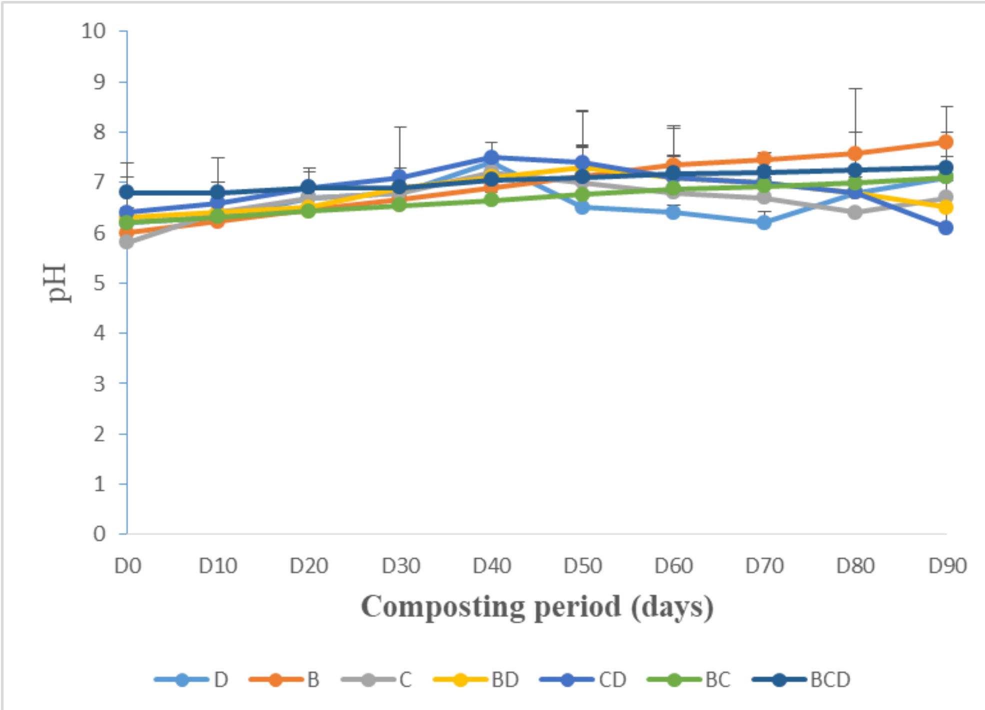


Fig.2 Variation in moisture content during the composting period

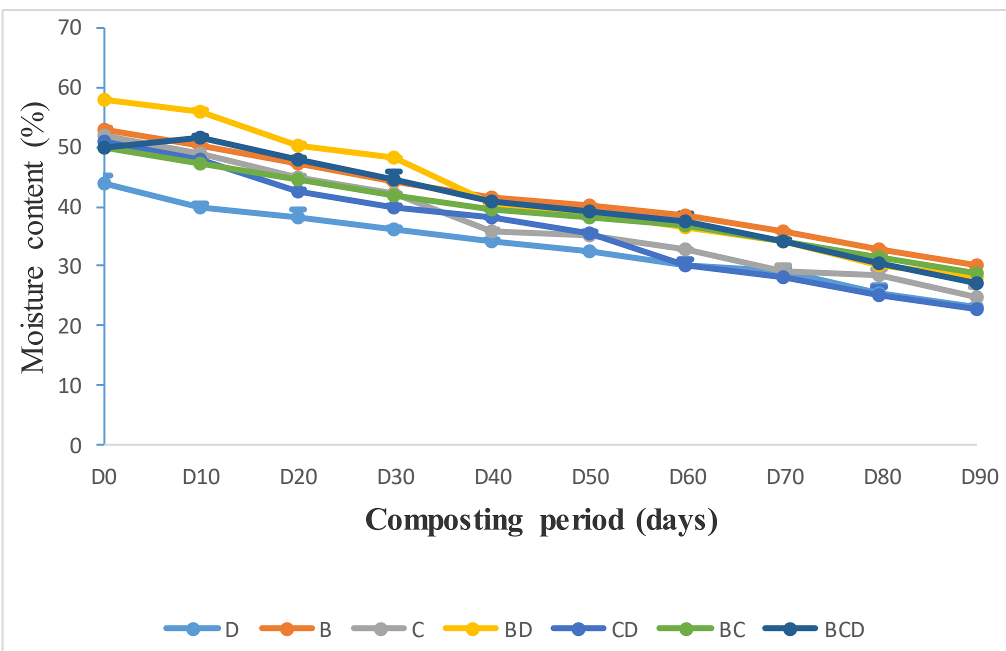


Fig.3 Variation in temperature during the composting period

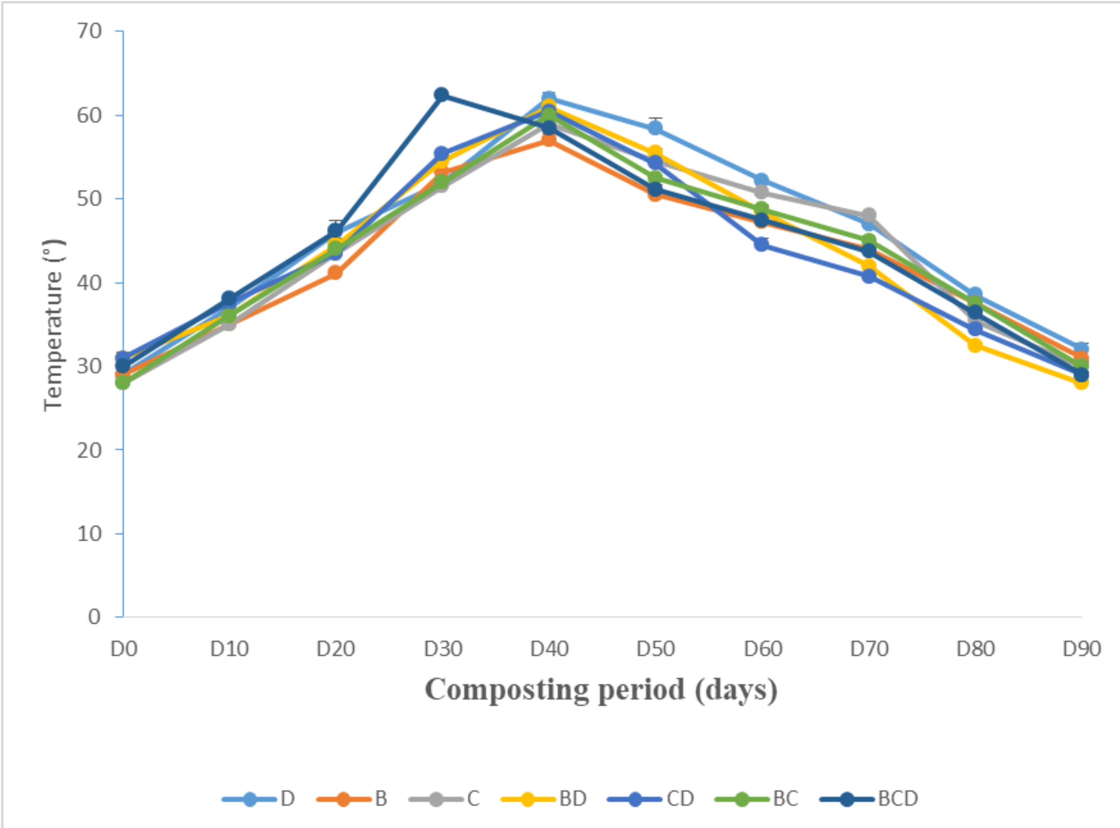


Fig.4A Evolution of the micro-organism load in type 'D'compost

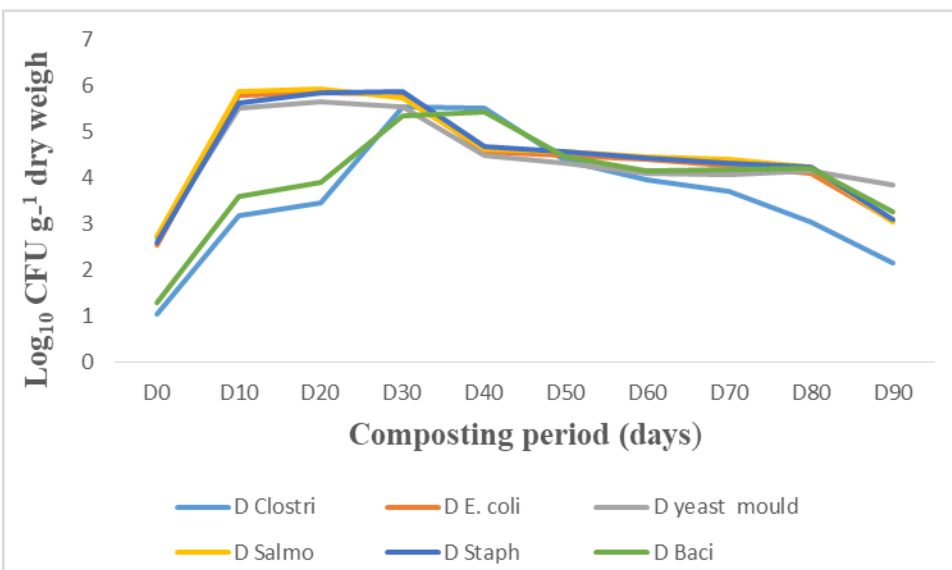


Fig.4B Evolution of the micro-organism load in type 'C'compost

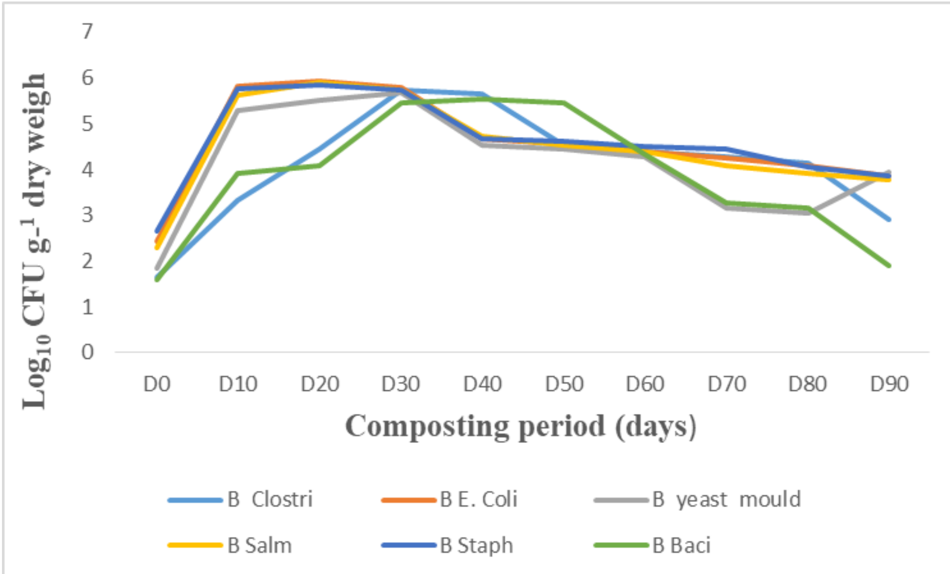


Fig.4C Evolution of the micro-organism load in 'C' compost

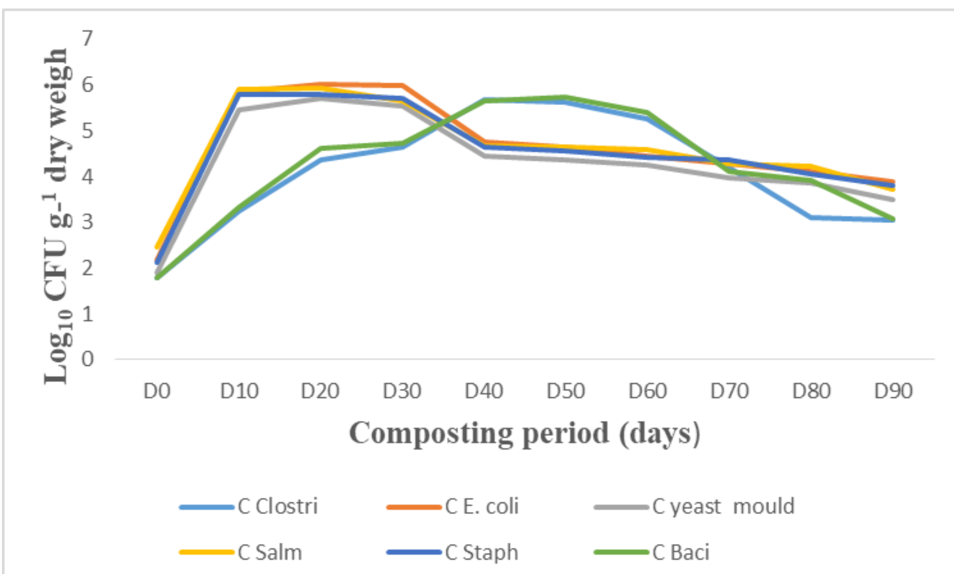


Fig.4D Evolution of the micro-organism load in 'CD' compost

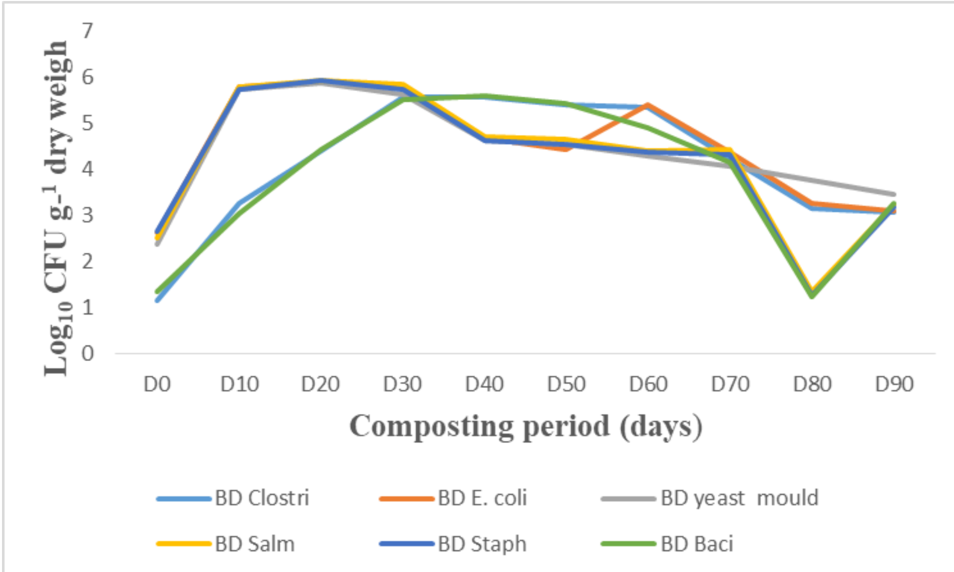


Fig.4E Evolution of the micro-organism load in 'CD' compost

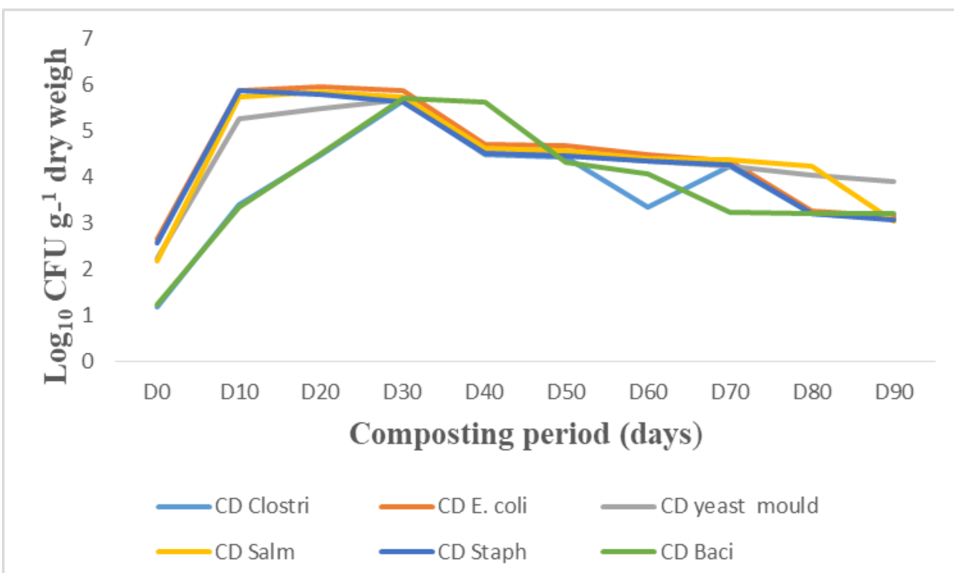


Fig.4F Evolution of the micro-organism load in 'BC' type compost

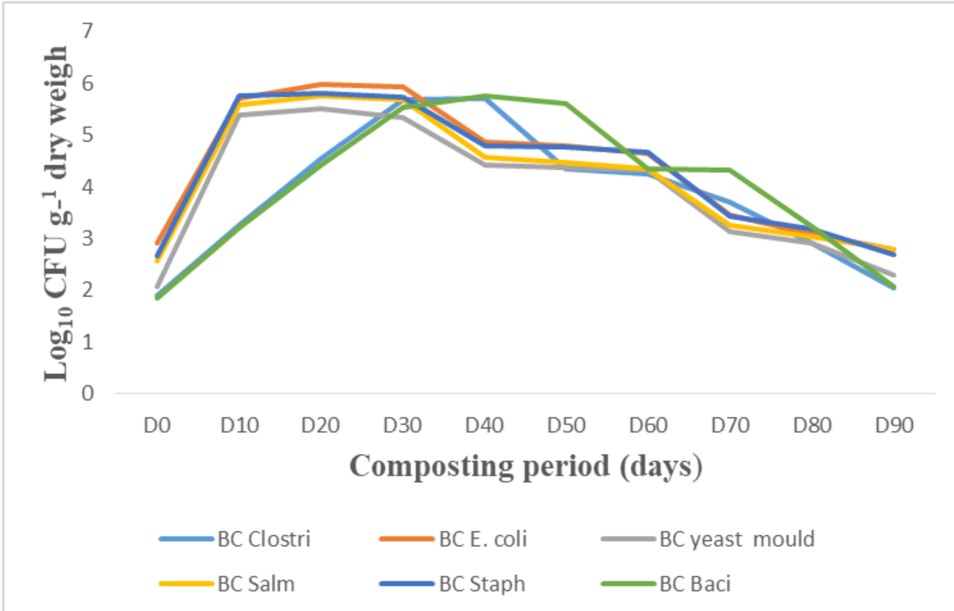


Fig.4G Evolution of the micro-organism load in 'BCD' compost

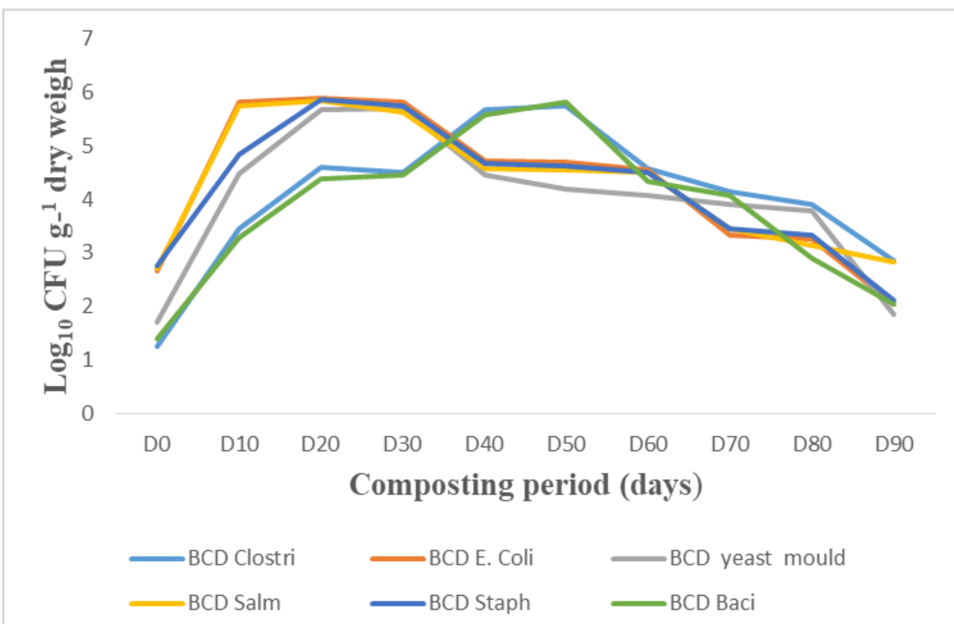


Fig.5A Distribution diagram of composts formulated with organic waste according to the F1 and F2 principal components of the PCA

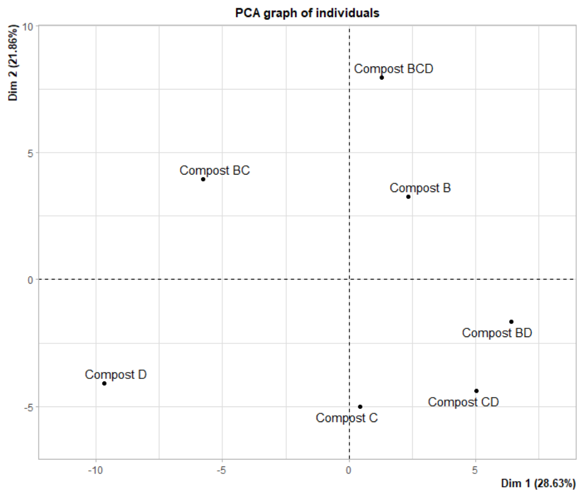


Fig.5B Dendrogram of formulated composts

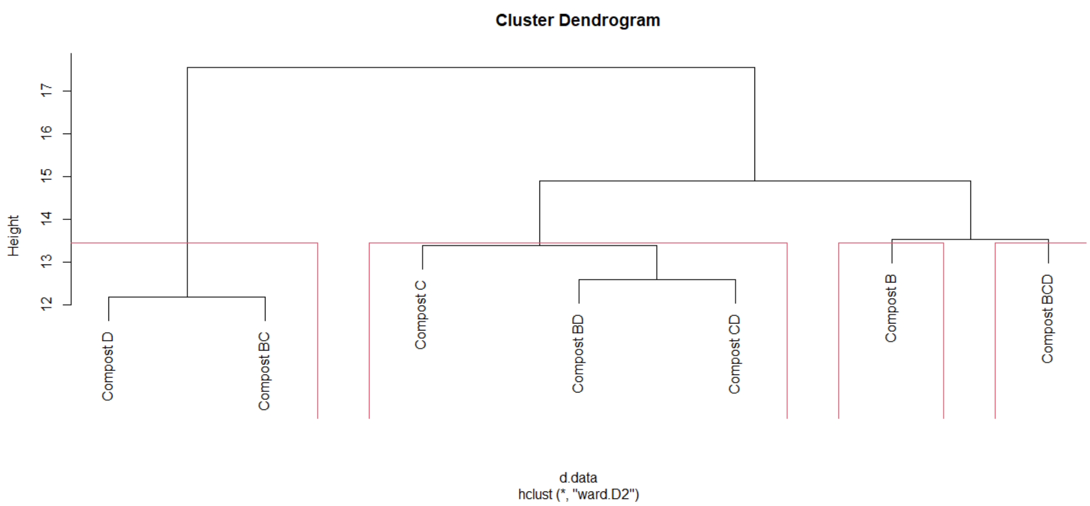
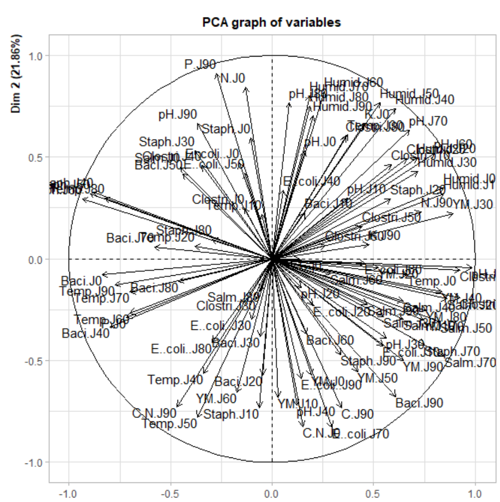


Fig.5C Biplot of formulated composts



For phosphorus, all the composts analysed had a low phosphorus content (between 0.084± 0.0% and 0.176±0) whereas the standard range established is between 0.3 and 0.9% in mature composts (Bazrafshan *et al.,* 2016).

Similar phosphorus levels have been determined in composts by several authors. Compaoré and Nanéma (2010) reported phosphorus levels well below 1% in compost made from municipal waste. Outende *et al.,* (2017) reported values of 0.36%, 0.45%, 0.26% and 0.38% respectively in green waste, green waste + food waste, green waste + limestone + clay waste and green waste + food waste + limestone + clay waste composts. Furthermore, phosphorus levels above 2% in cow dung (2.15%), poultry many (2.05%), rabbit droppings (2.15%) and cane rat droppings (3.3%) were determined by Kadir *et al.,* (2015) during the composting of food waste from Makanan Ringan in Malaysia.

The low phosphorus content of the composts analysed may be due to several factors. The composition of substrates such as banana peel (banana peel: 0.207± 0.0%) and cassava peel (cassava peel: 0.184± 0.0%), which are often low in phosphorus, directly influences its final concentration (Lanno *et al.,* 2021). Composting can transform phosphorus into less soluble forms under the effect of high temperatures, such as the 60°C observed in some composts, excessive humidity or an unsuitable pH, such as the acid pHs reported (5.6-6.8). Insufficient aeration also limits its uptake by micro-organisms, while its fixation by minerals such as calcium, magnesium or iron reduces its availability. What's more, an excessively high C/N ratio slows down organic degradation, slowing the release of phosphorus.

Optimised composting management, including a balanced pH, good aeration and adequate duration, is essential to maximise the availability of nutrients, particularly phosphorus. Most recently, Linlin *et al.,* (2023) used phosphorus solubilising bacteria (PSB) to increase phosphorus content in order to remedy poor phosphorus conversion during composting of spent mushroom substrate (SMS).

As for the standard range for potassium, it is between 0.5 and 1.5% and only type ‘M’ (0.924±0.2%) and ‘BD’ (0.92±0.1%) composts were within this range. Similar potassuim levels were reported by Tibu *et al.,* (2019) in composts from commercial waste with additive materials in Ga West Municipality, Ghana. However, Yélémou *et al.,* (2020) reported potassium levels well below 1% in compost made from Piliostigma reticulatum biomass in Bukina Faso. This difference in potassium content may be related to the composting technique and the type of raw material used for composting.

The low concentration of potassium in these designed composts may be the result of several factors linked to the nature of the raw materials and the composting conditions. The initial potassium content depends on the materials used, with some plant waste (straw, maize stalks, bark and dead leaves) being naturally low in this nutrient. This was the case for banana and manioc peelings in the present study, with potassium contents of 0.207± 0.0% and 0.184± 0.0% respectively. Moreover, potassium can bind to recalcitrant organic compounds or poorly soluble minerals, thus limiting its bioavailability to plants. Excessive humidity also encourages potassium leaching, while high temperatures such as the 60°C observed in some composts, while accelerating organic decomposition, can degrade the compounds that retain this nutrient. Finally, a non-optimal pH reduces the compost's ability to retain potassium, with a pH below 6 reducing cation exchange sites and a pH above 8 leading to the precipitation of insoluble forms.

Proper management of humidity, temperature and pH, combined with the use of potassium-rich raw materials and additives, is essential to limit potassium losses and obtain quality compost capable of meeting nutritional requirements (Waqas *et al.,* 2023).

Potentially pathogenic microorganism load in composts

To assess the microbiological quality of the composts, the evolution of the microbial load of the different composts was compared over a period of 90 days, as shown in Figujres 4 A-F.

This comparison of the microbial load of the different composts made it possible to assess the effectiveness of each type of compost in reducing the load of potentially pathogenic microorganisms, such as Clostridium, E. coli, Yeasts, Salmonella, Staphylococcus and Bacillus, and to determine which compost performed best in terms of reducing the microbial load. E. coli, Yeast, Salmonella, Staphylococcus and Bacillus, and to determine which compost performed best in terms of reducing the microbial load and microbiological safety.

For example, type ‘A’ compost (Clostridium: from 1.041 (log10) to 2.146 log10 CFU/g, at D90;.E. coli: from

2.544 to 3.079 log10 UFC/g at J90; Yeasts and Moulds: from 2.698 log10 to 3.845 log10 UFC/g at J90; Salmonella: from 2.740 to 3.041 UFC/g log10 at J90; Staphylococcus: 3.113 log10 CFU/g at D90; Bacillus: 1.301 to 3.255 log10 CFU/g at D90) reduced pathogenic microorganisms, but the reduction was relatively slow, and some microorganisms, such as Clostridium and E. coli, remained at relatively high levels at the end of the observation period, with values of 2.146 log10 CFU /g and 3.079 log10 CFU /g respectively.

Type 'B' compost (Clostridium: from 1.643 (log10) to 2.903 log10 CFU/g at 90 days; E. coli: from 2.431 to 3.845 log10 CFU/g at D90; Yeasts and Moulds: from 1.845 log10 to 3.954 log10 CFU/g at D90; Salmonella: from 2.278 to 3.778 log10 CFU/g at D90; Staphylococcus: 2.643 to 3.845 log10 CFU/g at D90; Bacillus: 1.602 to 3.255 log10 CFU/g at D90,) showed a higher capacity to reduce the microbial load, particularly for E. coli, Yeast and Bacillus, compared with type 'A' compost. However, the reduction in the clostridium and salmonella load remained relatively less marked, with values of 2.903 log10 CFU /g and 3.778 log10 CFU /g respectively still notable at D90. As for type 'C'compost (Clostridium: from 1.778 (log10) to 3.041 log10 CFU/g at D90; E. coli: from 2.176 to 3.875 log10 CFU/g at D90; Yeasts and Moulds: from 1.903 to 3.505 log10 CFU/g at D90; Salmonella: from 2.447 to 3.732 log10 CFU/g at D90; Staphylococcus: from 2.113 to 3.812 log10 CFU/g at D90; Bacillus: from 1.778 to 3.079 log10 CFU/g at D90). It showed the best performance in terms of reducing the load of pathogenic microorganisms.

Loads of Clostridium (3.041 log10 CFU/g), E. coli (3.875 log10 CFU/g) and Bacillus (3.079 log10 CFU/g), among others, were particularly low at D90, indicating a faster and more effective reduction in microorganisms.

BCD compost (Clostridium: from 1.643 (log10) to 2.845 log10 CFU/g at D90). E. coli: from 2.662 to 2.041 log10 CFU /g at D90; Yeasts and Moulds: from 1.698 log10 to 1.857 log10 CFU /g at D90; Salmonella: from 2.301 to 3.170 log10 CFU /g at D90; Staphylococcus: from 2.123 to 3.341 log10 CFU /g at D90; Bacillus: from 1.903 to 3.341 log10 CFU /g at D90,) is the compost that offers the best performance in terms of rapid and effective reduction of most microorganisms, particularly pathogens such as Salmonella, *E. coli*, Staphylococcus and Clostridium. It appears to offer faster reduction and stabilisation at very low levels of pathogenic microorganisms. It offered the best results in terms of overall microbial load reduction, ranking as the most effective compost in this study. However, as indicated, the load of certain indicator micro-organisms such as Escherichia coli and Salmonella in BCD compost ranged from 2.041 log10 CFU/g to 3.170 log10 CFU/g, which does not generally meet French requirements for organic fertilisers (AFNOR NF U 44-051; less than 10^2/g MB Escherichia coli and no Salmonella). In these mature composts, the load of indicator microorganisms was detected in a range exceeding the value recommended for unrestricted application of municipal solid waste compost. Indeed, the absence of Salmonella as a frank human pathogen is very important in assessing the efficiency of the composting process and the sanitary quality of the compost, and therefore the potential health risks. The presence of this pathogen in finished products leads to the hypothesis of shortages in the composting process (Lemunier *et al.,* 2005).

In general, all the composts analysed showed a reduction in pathogenic micro-organisms such as E. coli and Staphylococcus by day 90, but the persistence of Clostridium and Salmonella in all the composts, whatever their maturity, at relatively high concentrations, suggests that composting was not totally effective in eliminating these pathogens. This phenomenon can be attributed, as Gurtler *et al.,* (2018) pointed out, to the slow degradation of the organic matter or to a lack of optimal conditions (aeration, temperature, etc.) for destroying these micro-organisms. These observations indicate that organic composts containing rabbit detritus may constitute a potential refuge for food-borne pathogens. Furthermore, the persistence of Salmonella and Clostridium has been observed in composts produced on small and medium-sized poultry farms in South Carolina (Shepherd *et al.,* 2010), in organic fertilisers (some of which included manure and/or compost) (Miller *et al.,* 2013) and in point-of-sale composts from 94 composting facilities (Brinton *et al.,* 2009), reflecting the ability of these pathogens to survive in organic substrates even after composting.

Although the overall microbial load of composts is reduced, the persistence of pathogens such as Clostridium and Salmonella calls into question the effectiveness of composting. The inactivation of pathogens relies primarily on the achievement of high temperatures (>55°C) generated by indigenous microbial activity in self-insulating materials. However, several factors can prevent these critical temperatures from being reached: a high surface-to-volume ratio leads to significant heat loss, an initial microbial population that is insufficient or poorly balanced in terms of carbon and nitrogen limits heat production, and unfavourable ambient temperatures accelerate thermal dissipation. In addition, the slow degradation of organic matter, insufficient duration of the process, thermal heterogeneity due to a lack of stirring, and the risk of post-composting contamination (storage, transport, handling) also contribute to the persistence of pathogens (Gurtler *et al.,* 2018).

Moreover, non-thermal factors, such as the action of antagonistic agents, desiccation, or the influence of chemical compounds (volatile acids, ammonia), can play a role in pathogen inactivation. Studies have shown, for example, that in the composting of cow manure enriched with wood chips or straw, the reduction of total coliforms (from 7.86 to 1.69 log CFU/g in 14 days) occurs before reaching maximum temperatures (66.7 to 68.7°C) (Larney *et al.,* 2003). Similarly, research by Erickson *et al.,* (2013, 2014, 2015a, 2015b) demonstrated that optimizing physical parameters (temperature, light exposure) and chemical parameters (manure source and age, C:N ratio, pH) enables reproducible and rapid non-thermal inactivation of pathogens.

Thus, the sanitary quality of compost depends on the simultaneous optimization of thermal and non-thermal parameters, from the selection of inputs to post-composting management, to ensure a product that meets health standards and is free of pathogens.

Principal component analysis of the characteristics of formulated composts

In an attempt to simplify the interpretation of the data, Principal Component Analysis (PCA) was used to classify the different composts produced, identify the key factors influencing their quality, and predict their agricultural use based on their state of degradation, nutrient content and load of potentially pathogenic microorganisms (Figures 5A-C).

The two principal components explained 73.22% of the variation in the data, with the first component (axis 1) accounting for over 46.80% of the variation and the second component (axis 2) for 26.42% of the variation. Axis 1 (46.80%) is mainly associated with biological degradation, influenced by parameters such as high temperature, low C/N ratio, and a high load of pathogenic and potentially pathogenic micro-organisms. Axis 2 (26.42%) appears to capture variations related to the nutritional composition of the composts, in particular the C/N ratio and the nutrient content (NPK). This PCA followed by a Hierarchical Ascending Classification (HAC) and a biplot was also used to classify the formulated composts into three groups to predict their potential agricultural application: group 1 composts, group 2 composts and group 3 composts. Group 1 composts (young composts undergoing active degradation: D, BC), characterised by a low C/N ratio, a modest NPK content, a slightly acid pH and a high load of potentially pathogenic micro-organisms, are positively correlated with axis 1. These composts require additional treatment to reduce the load of potentially pathogenic micro-organisms and balance their chemical composition before use in agriculture. They are at an active stage of degradation and are not yet ready for agricultural use without further treatment.

Group 2 composts (mature and well-degraded composts: C, BD, CD) are positively correlated with axis 2, and are characterised by a low temperature, a high NPK content, a neutral or slightly acid pH, and a low load of potentially pathogenic micro-organisms. These composts are mature, safe to use, and rich in nutrients.

This group is particularly suitable for use as an agricultural amendment, as they are ready to improve soil fertility. In contrast to group 2 composts, characterised by low temperature and high NPK content, group 3 composts (intermediate composts: B, BCD) were characterised by moderate temperature, an intermediate load of potentially pathogenic microorganisms and average NPK content.

These composts have intermediate characteristics. Their degradation is not complete and their pathogenic load is higher than that of Group 2 composts. They may contain more soluble sugars, but are still a long way from being mature enough to be used without precautions. This group requires specific interventions before it can be used optimally in agriculture.

In conclusion, this study highlighted significant results concerning the quality of composts and their optimal management. The findings show that the nitrogen, phosphorus, and potassium content of the analyzed composts varies considerably. Specifically, the nitrogen content remains relatively stable, but notable losses have been observed, with levels ranging from 0.924% to 1.5%, which are below the optimal standards (2 to 5%). The low phosphorus content in the composts, ranging from

0.084±0.0% to 0.176±0.0%, is significantly lower than the standard range of 0.3 to 0.9% for mature composts. Regarding potassium, only the "M" (0.924±0.2%) and "BD" (0.92±0.1%) compost types fall within the standard range of 0.5 to 1.5%. From a microbiological perspective, the "BCD" type composts showed the best performance in terms of pathogen reduction, with Clostridium and E. coli counts at day 90 reduced to 2.845 log10 and 2.041 log10 CFU/g, respectively. However, these levels remain higher than the French safety requirements (less than 102 CFU/g of E. coli). This indicates that, although the microbial load has been reduced, the persistent presence of pathogens like Clostridium and Salmonella still poses a potential risk to the safety of the composts.

To improve the effectiveness and safety of composting, it is essential to:

Maintain a constant temperature of 55°C to 60°C to ensure the destruction of pathogens. Improving aeration and pH (ideally between 6 and 7) will also promote better nutrient availability, particularly phosphorus;

Extend the composting duration to ensure complete elimination of pathogens and stabilization of nutrients;

Increase the composting duration further to further reduce pathogen load and improve nutrient stability, thus ensuring the safety of the final product.

This study underscores the importance of rigorous composting process management to ensure compost quality, both from a nutritional and microbiological perspective.

Although improvements are needed, particularly regarding phosphorus content and pathogen reduction, the recommendations provided to optimize composting conditions can help achieve higher-quality composts that are safe for the environment and public health.

Author Contributions

TRA Bi Youan Charles: Conceived the original idea and designed the model the computational framework and wrote the manuscript; TOURE Mamadou: Formal analysis, writing review and editing; KOUAME Kohi Alfred,: Validation, methodology, writing—reviewing; BOUATENIN Koffi Maizan Jean-Paul: Formal analysis, writing review and editing; Lassina TRAORE: Validation, methodology, writing—reviewing; Ange Christine DJOHORE: Formal analysis, writing review and editing and AKA Boko: Validation, methodology, writing—reviewing.

Declarations

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