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Assessing the Amending and Fertilizing Properties of Digestates From Anaerobic Digestion of Faecal Sludge in Burkina Faso, West Africa

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Abstract

The aim of this work is to contribute to the agronomic utilization of digestate from the anaerobic treatment of faecal sludge at the Office National de l'Eau et de l'Assainissement (ONEA) Kossodo plant in Burkina Faso. Digestates were sampled and dried in the laboratory (25±2 °C). Physico-chemical and microbiological parameters were determined using standard methods. The degree of maturity of the digestate was determined using respirometry and humification tests. The effects of digestate on plants and on environment were studied using phytotoxicity, emergence, growth tests and microbiological analysis. The results revealed a pH of 8.54, electrical conductivity of 7300 µS/cm, 25.42% dry matter, 83.31% organic matter, and 489.8 g/kg total organic carbon. The C/N ratio was 9.7 and the NO_3/NH_4 ratio was 23.34, indicating mature compost despite other indicators suggesting that the digestate was only partially stabilized. Nutrient contents were 50.48 g/kg total nitrogen, 0.02 g/kg total phosphorus, and 4.72 g/kg total potassium. Water-soluble minerals included 1.97 g/kg ammonium, 45.99 g/kg nitrate, 0.02 g/kg nitrite, 0.35 g/kg phosphate, and 5.90 g/kg sulfate. Phytotoxicity tests showed that cabbage seeds had a germination rate of 89% with digestate filtrate compared to 100% in the control, while tomato seeds had a 100% germination rate with digestate filtrate. The germination indices were 137.58 for tomato and 82.10 for cabbage. Tests on tomato plant growth showed significant effects on biomass, height, leaf number, and branch number, with the 50% digestate proportion demonstrating the highest values. Microbiological analysis detected total aerobic flora at 4.75E+07 CFU/g, yeasts and molds at 7.77E+04 CFU/g, and coliforms at various levels, with potential pathogens such as *S. aureus* and *Salmonella* sp. reaching 6.14E+04 and 2.65E+06 CFU/g respectively. The presence of these pathogens suggests a need for further treatment of digestate to ensure safety before field application.

Keywords: faecal sludge, anaerobic digestion, digestate, agronomic use, microbiology, Kossodo, Burkina Faso

1. Introduction

In 2021, approximately 3.6 billion people or 46% of the global population lacked access to safely managed sanitation as outline in Target 6.2 of the Sustainable Development Goals (SDGs) (UN-WATER, 2023). Of these, 1.7 billion people endure the indignities and risks associated with unsafe and inadequate toilets. or lack access to a toilet altogether. The remaining 1.9 billion use toilets that fail to contain and/or treat human waste. resulting in contamination of both people and the environment, with serious health and economic consequences. According to the World Health Organization (WHO), over 2 billion people rely on autonomous sanitation systems but lack access to suitable and effective management for faecal sludge (UNICEF & OMS, 2020). Sewage systems generate large quantities of sludge. According to Tilley et al. (2009), faecal sludge is the solid waste from toilets. Its composition depends on where it is produced. The water content and storage affect it. In Europe, France produces 0.85 million tonnes/year of sludge and Germany 2.7 million tonnes/year (EL Fels, 2023). The rapid population growth in African cities coupled with the rise of informal settlements makes waste management and urban sanitation particularly complex challenges. According to Strauss et al. (2002), in Africa 65% to 100% of households with sewage systems rely on independent installations that are not connected to a sewer network. The city of Kumasi in Ghana produced around 300-400 m^3/day in 1993 (Heinss et al., 1998). The town of Aného in Togo will produce between 3534 and 7442 m^3 per year in 2020 (Poromna et al., 2020). Bamako in Mali, produces 600.000 m^3 of mud a year. In Dakar (Senegal), the sludge deposit was 15.000 m^3 per day (Tadjouwa, 2017). Since 2016, sanitation in Burkina Faso has been governed by the National Wastewater and Excreta Sanitation Programme (Programme National d'Assainissement des Eaux Usées et Excréta-PN-AEUE) aligning with the vision outlined in Target 6.2 of the Millennium Development Goals (MDGs). The city of Ouagadougou generates an average of 1.000 m^3 of faecal sludge daily, particularly during the winter season when demand peaks due to rising groundwater levels in certain low-lying areas. However, as of 2018, the combined capacity of the three faecal sludge treatment plants (STBV) is only estimated at 385 m^3 per day (SPONG, 2020). Studies by Gouba et al. (2022) estimate that overall wastewater discharge in arrondissement 4 (Kossodo) of Ouagadougou Burkina Faso, with a population of 180.428 will reach approximately 44.116 m^3/d per day by 2025 and 233.176 m^3/d per day by 2050. Additionally in Burkina Faso, daily sludge production in Ouahigouya town is estimated at 31.3 m^3 (Tall, 2019). Daily sewage sludge production in the communes of Dano and Diébougou was estimated at 49 m^3 (Blunier et al., 2004). Wastewater treatment is a purification process that encompasses a variety of services including storage emptying transport treatment and Recovery. Faecal sludge treatment plants have been established throughout the country. They can be found in most of the major towns including Ouagadougou, Bobo Dioulasso, Koudougou, Ouahigouya, Fada N'Gourma and Dori. Various technologies have been developed to treat faecal sludge including drying beds and sedimentation/thickening tanks composting and anaerobic digestion (Lo et al., 2019; Kouawa, 2016). Sludge drying beds can be either planted or unplanted. These shallow basins are filled with sand and gravel and feature equipped a drainage system that collects percolate, allowing the sludge to dry on surface of the bed (Tagba, 2019). Sedimentation and thickening tanks are designed to thicken sludge by allowing solids to settle. The supernatant is then discharged to a subsequent treatment facility. Co-composting sewage sludge with co-substrates of animal and plant origin enhances the agronomic potential of the sludge while simultaneously protecting people from the risks associated with its reuse (Lo et al., 2019). The aim of composting digestate is to stabilize it, break down the recalcitrant carbon in the solid fraction and eliminate as many pathogenic micro-organisms as possible (Bustamante et al., 2013). Anaerobic digestion is the initial step in sludge treatment following the decantation phase facilitating the handling of sludge regardless of its final destination: whether for agricultural use incineration, landfilling or any intermediate treatments such as dehydration liming thermal drying or composting (Couturier et al., 2001). According to Doublet et al. (2004), studies on digestate from anaerobic sludge digestion indicate reduction in dryness, leading to improvement fluidity compared to original substrate. This enhancement can have positive agronomic effects by facilitating the infiltration of digested slurry into the soil. Le Bihan et al. (2013) have reported that the liquid fraction of digestate is similar to a mineral fertilizer and shares characteristics with pig slurry. Elalami et al. (2022) applied sludge digestates as biofertilizers for tomato growth during the first vegetative stage. Sludge digestate addition to tomato plants resulted in chlorophyll a and carotenoid concentrations increase by 46% and 41% respectively. Furthermore, the dry weight of the tomato plants increased by 87% and the nitrogen content increased by 90%. (Slepetiene et al., 2020) showed that solid digestate improves soil quality, sustainability and durability. Adding P_2O_5 and nitrogenous forms increases soil fertility from 'high' to 'very high'. It also increases the quantity of mobile humic acids by 1.6 times in the 0-40 cm soil layer. The solid fraction of digestate from anaerobic digestion units does not meet current regulations for use on agricultural land (Bustamante et al., 2013). It is therefore imperative to gain an understanding of the properties of the digestate prior to its application to agricultural fields, in order to facilitate informed decision-making with regard to the most appropriate post-treatment option (Teglia et al., 2011). According to Doublet et al. (2004), understanding the impact of digestion on the agronomic and sanitary value of organic matter as well as the effects of digestates on the biological physical and chemical properties of soils is crucial. Ezemagu et al. (2021) found that the final sludge compost contains trace elements of zinc (Zn), chromium (Cr), copper (Cu), cadmium (Cd) and lead (Pb), within the recommended limits for use in agriculture. (Di Maria et al., 2014) showed that digestate can harm plants when used in large amounts. The digestate had higher organic nitrogen and carbon concentrations, despite the germination index showing that it was not suitable for farming. In their review, Nkoa (2013) identified several potential issues associated with digestate, including odour emissions, toxic chemicals, pathogens and plant damage. Teglia et al. (2011b) have reported that the sustainability of anaerobic digestion is contingent upon the management of these digestion residues. The specific characteristics of digestates could reduce their direct agricultural use. The Kossodo plant includes 2,500 m^3 digester and a secondary tank for the potential recovery of biogas during the maturation phase of anaerobic sludge treatment. The digestate from the covered digester is a fine sludge with potentially interesting characteristics for agriculture. This study aims to contribute to the improvement of the recovery of digestate from the anaerobic treatment of sewage sludge by assessing its agronomic and health characteristics.

2. Materials and Methods

2.1 Origin of Digestate

The sample was taken from a sewage sludge treatment and recovery site in Kossodo, Ouagadougou, Burkina Faso. The samples were placed in bags and put in a cooler with ice. The sewage sludge treatment plant at Kossodo has twenty-eight (28) drying beds (95 m^2 each). The total area of the facility is 2,660 m^2, comprising two digesters: 2,500 m^3 digester and 1,300 m^3 maturation tank. The latter is designed to produce biogas from sewage sludge. Figure 1 illustrates the fine sludge production process. After deposition fresh faecal sludge undergoes pre-treatment to remove coarse elements and sand. The pre-treated sludge is then subjected to anaerobic digestion in the 2.500 m^3 digester. The pre-treated sludge is then subjected to anaerobic digestion in the 2.500 m^3 digester. The liquid digestate is subsequently transferred to the 1300 m^3 maturation tank digester to facilitate maturation and recover the residual biogas. Fine sludge was accumulated in the pit of tank digester where it can be harvested.

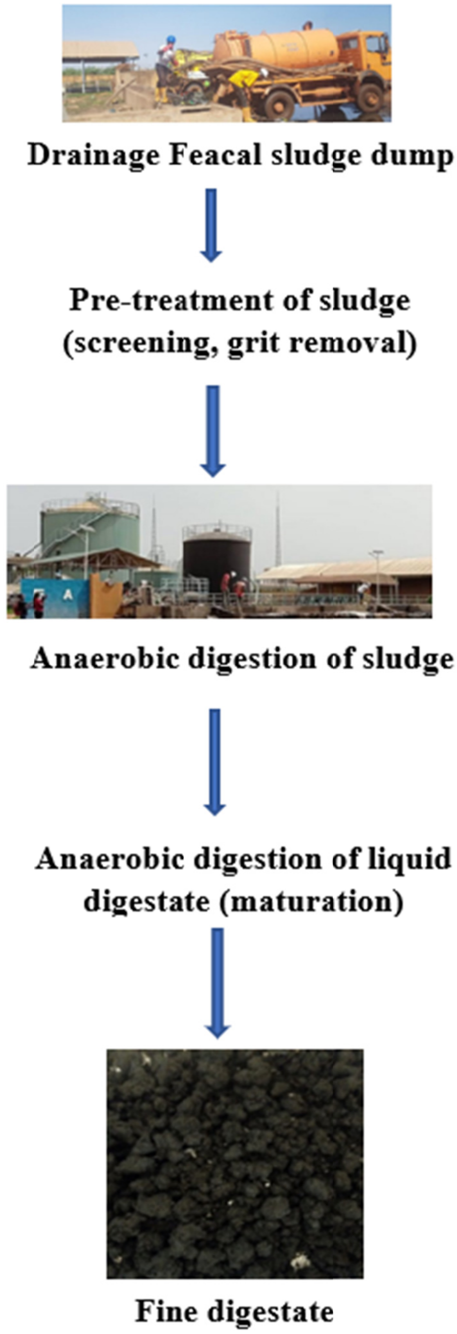

Figure 1. Diagram of fine digestate production

2.2 Chemical Analysis of Digestate

pH and electrical conductivity were determined using a 1/10 (w/v) extract of the digestate (Ofosu-budu et al., 2010). The dry matter (DM) content was determined by drying a 5 g test sample in an oven at 105 °C for 24 hours, until a constant weight was achieved. The dried samples were placed in an oven at 550 °C for 6 hours to determine ash content. Organic matter was calculated as the difference between dry matter and ash content. Total carbon (Ct) was derived from the theoretical organic matter ratio, which is generally estimated to be 1.724 according to Van Bemmelen (1890). Total nitrogen was determined using the Kjeldahl method as described by Bremner (1965) and reported by (Afilal et al., 2014). Total potassium was measured using an AAS VARIAN 240 FS atomic absorption spectrophotometer, following the methodology of (Demirel & Scherer, 2008). Soluble nitrogen compounds (NO_2^-, NO_3^-, NH_4^+) and phosphorus compounds (PO_4^{3-}) were determined using a HACH

DR/1900 spectrophotometer. as outlined in method (APHA, 2017). Organic nitrogen (Norg) in digestates was calculated as the difference between total Kjeldahl nitrogen (TKN) and ammoniacal nitrogen (NH_4^+-N).

2.3 Assessment of Digestate Maturity and Stability

The respirometry test was conducted using the modified method of Germon (1986). A 100 g sample of moistened digestate was placed in 300 ml septum-capped flasks. The flasks were hermetically sealed and incubated at room temperature (25±2 °C). The volume of gas produced, expressed as CO_2, was measured using a liquid displacement technique adapted from Esposito et al. (2011). The degree of humification was assessed by evaluating the color of the humus using the method reported by Ofosu-Budu et al. (2010). The absorbance of alkaline digest extracts was measured at 400 and 600 nm using a spectrophotometer.

The change in absorbance (log K value) was calculated as follows: $\log K = \log(K_{400}/K_{600}) = \log K_{400} - \log K_{600}$, where, K_{400} and K_{600} represent the absorbances at 400 and 600 nm respectively (Morel, 1982). Phytotoxicity was assessed using the germination test described by Zucconi et al. (1981).

Two varieties were used for the tests: tomato (*Lycopersicum esculentum* L. Var. Tropimech) and KK Cross F1 cabbage marketed by TECHNISEM. An extract of the digestate was prepared in a 1:5 (w/v) ratio of digestate and distilled water for 1 hour, then filtered. A volume of 15 ml of the digestate extract was used to moisten each Petri dish lined with Whatman paper. Ten seeds were then placed in each Petri dish which were sealed and kept in the dark at ambient conditions (25±2 °C) for 7 days. The germination percentage was recorded at three intervals: 96 hours, 144 hours, and 184 hours (Beauchemin et al., 1992). At the end of the observation period, the length of the radicles was measured. The percentage of seed germination, root elongation rate, germination index (GI) and germination speed (T50) were calculated according to Equations 1-4:

$$\text{Germination rate} = \text{No. of grains germinated in the digestate/No. of grains germinated in the control} \times 100 \quad (1)$$

$$\text{Root elongation rate} = \text{Length of root germinated in digesta/Length of root germinated in control} \times 100 \quad (2)$$

$$GI = \text{Germination rate} \times \text{Root elongation rate}/100 \quad (3)$$

Germination rate (T50) expressed as the number of seeds germinated per unit time according to the equations of Bae et al. (2016).

$$T50 = ti + (N/2 - ni)\ (ti - tj)/(ni - nj) \quad (4)$$

where, N: total number of seeds germinated during 7 days; ni, nj: cumulative number of germinated seeds at respective times ti and tj measured in hours with $ni < N/2 < nj$.

The emergence and growth test were carried out using the method described by Pivato et al. (2016) with tomatoes as the crop. The trials were carried out in a natural tropical climate to study the early stages of leaf growth. Six (06) pots with a volume of 33 cl were filled with 300 g of substrate. Six (06) different concentrations of digestate (0%, 5%, 25%, 50%, 75% and 100%) were mixed with sterile sand for analysis (Pivato et al., 2016). The experiments were conducted in triplicate. Seedlings that had germinated in trays of uniform size were selected and transplanted into pots 14 days after sowing. The transplanted seedlings were irrigated with distilled water at a rate of 30ml per occasion, twice daily for the first four weeks. The development of the seedlings was monitored by measuring the increase in height of the aerial part and the number of leaves at seven-day intervals over a period of one month (M'Sadak & Ben M'Barek, 2016).

2.4 Pathogen Detection in Digestate

The total aerobic flora was determined using the Most Probable Number (MPN) method. This method was also used to determine the number of presumptive Salmonella after pre-enrichment of the digestate in peptone water, followed by enrichment with Rappaport Vassiliadis and plating on SS agar. The black colonies observed are presumed to be Salmonella. Other types of microorganisms were counted after plating dilution series on solids in Petri dishes. Coagulase-positive, including Staphylococcus aureus and other species, were enumerated on Baird-Parker agar containing potassium tellurite egg yolk. Yeasts and fungi were enumerated on Sabouraud chloramphenicol agar incubated at 30 °C for 3-5 days. Total coliforms and thermotolerant coliforms were quantified on methylene blue and eosin media incubated at 37 °C and 44 °C respectively. The observed colonies were counted and expressed as colony forming units per gram (cfu/g) according to Equation (5) (El Asri et al., 2020):

$$N = \frac{\Sigma C}{Vi \cdot (1.1) \cdot d} \times Fd \quad (5)$$

where, N is the number of colony-forming units per gram (cfu/g). ΣC = Sum of colonies. Vi = volume inoculated. d = First dilution. Fd = dilution factor for digestate.

2.5 Statistical Analyses

Data analysis was processed with XLSAT software version 2018. An analysis of variance (ANOVA) was carried out to compare the mean values of the different variables using the Fisher LSD tests at probability p = 5%.

3. Results

3.1 Chemical Analyses

Table 1 shows the chemical and physical properties of the digestate from the sampled faecal sludge at Kossodo. The pH was 8.54 and the conductivity was 7300 µS/cm. The digestate had 83.31% organic matter. The total organic carbon was 489.8 g C/kg DM. The nitrogen content was 50.48 g/kg DM, phosphorus was 0.02 g/kg DM and potassium was 4.72 g/kg DM. The soluble element contents were 1.97 g/kg DM for ammonium, 45.99 g/kg DM for nitrate, 0.02 g/kg DM for nitrite, 0.35 g/kg DM for phosphate (P_2O_5), and 5.90 g/kg DM for sulfate (SO_4^{2-}). The mineral contents of iron and manganese were 5.80 g/kg DM and 1.18 g/kg MS.

Table 1. Physicochemical parameters of the digestate

Parameters	**Unity**	**Averages**
pH	-	8.54±0.02
Electrical conductivity	µS/cm	7300±0.05
MS	%	25..42±1.7
MO	% MS	83.31±1.3
COT	g/Kg MS	489.8±0.7
Nt	g/Kg MS	50.48±6.49
Pt	g/Kg MS	0.02±0.004
Kt	g/Kg MS	4.72±0.00
NH_4^+	g/Kg MS	1.97±0.83
NO_3^-	g/Kg MS	45.99±1.80
NO_2^-	g/Kg MS	0.02±0.00
$P_2O_5^-$	g/Kg MS	0.35±0.08
SO_4^{2-}	g/Kg MS	5.90±0.00
N org	g/Kg MS	48.51
C/N	$g/Kg \cdot g/Kg^{-1}$	9.70±0.05

Note. MS: Dry matter. MO: Organic matter. TOC: Total organic carbon. N org: Organic nitrogen.

3.2 Assessment of Digestate Maturity and Stability

The maturity and stability parameters are presented in Table 2. The CO_2 emissions value was 5.26 g/Kg MS/d or 0.22 g/Kg MS/h. The nitrate to ammonium ratio is 23.34 and the determined degree of humification is 0.99. The ratio of total carbon to total nitrogen is 9.7.

Table 2. Maturity and stability parameter of digestat

Parameters	Unity	Averages
CO_2	g/Kg MS	5.26±1.17
NO_3^-/NH_4^+	-	23.34±0.83
Degree of humification	-	0.99±0.003

The results of germination test for two species, namely tomato and cabbage, are presented in Table 3. A total of 50 seeds of each species were subjected to germination testing, with the results compared between the digestate and the control. The control exhibited a 100% germination rate for cabbage seeds, while the digestate filtrate demonstrated an 89% germination rate. The germination rate for cabbage seeds in the control group was 100%, in contrast to the 89% observed in the digestate filtrate. The germination rate for tomato seeds was 100% in the digestate filtrate. The germination indices were 137.58 for the tomato seeds and 82.10 for the cabbage seeds. The average time required for half of the tomato seeds to germinate was 78.54 hours, whereas the same milestone was reached in only 47.16 hours for the cabbage seeds. The roots of tomato plants exhibited a significantly greater degree of elongation in the digestate treatment than in the control (distilled water), with an increase of 137.58%. The elongation rate for the cabbage plants was found to be 92.25%. The germination indices were 137.58 for tomato and 82.10 for cabbage, respectively.

Table 3. Germination test parameters

Parameters	Speculation	
	Tomato	**Cabbage**
Germination rate (%)	100	89
T50 (Number of seeds germinated per hour)	78.54	47.16
IG (%)	137.58	82.10
Root elongation rate (%)	137.58	92.25

Tomato emergence and leaf growth test at varying proportions of digestate (0%, 25%, 75%, 50%, and 100%) are presented in Table 4. The statistical analysis indicates a statistically significant effect of digestate proportions on above-ground biomass (AB). The results demonstrated a statistically significant effect of the experimental variables on both the height (H) and the number of leaves (F) ($p < 0.05$). The 50% digestate proportion demonstrated consistently high values for the majority of the measured parameters. Figure 2 presents images of tomato plants at the conclusion of the growth period, showcasing harmonious development in the 50% and 75% digestate treatments. The ratios of growth parameters between the digestate and the control indicate that the agromorphological parameters, including above-ground biomass, root biomass, height, collar diameter and number of leaves, achieve optimal ratios at 50% digestate. The ratios were recorded as follows: 7.87 for above-ground biomass, 2.25 for root biomass, 2.06 for height, 2.28 for collar diameter, and 4.00 for the number of leaves.

Table 4. Emergence and growth tests

Dose digestat	D100%	D75%	D50%	D25%	D5%	D0%	*p* value
BA(g)	0.027^{ab}	0.052^{bc}	0.063^{c}	0.044^{bc}	0.026^{ab}	0.008^{a}	0.016
BR(g)	0.001^{a}	0.008^{abc}	0.009^{abc}	0.021^{c}	0.019^{bc}	0.004^{ab}	0.111
H(cm)	9.667^{c}	10.167^{c}	10.667^{c}	8.333^{bc}	6.000^{ab}	4.667^{a}	0.01
D(cm)	0.767^{ab}	1.100^{b}	1.100^{b}	0.767^{ab}	0.767^{ab}	0.533^{a}	0.075
F	10.000^{ab}	14.000^{bc}	16.333^{c}	13.333^{bc}	11.333^{abc}	6.000^{a}	0.019
R	2.000^{ab}	3.667^{c}	4.000^{c}	3.333^{bc}	2.667^{bc}	1.000^{a}	0.006
R(BA)	3.4	6.5	7.9	5.5	3.3	1	-
R(BR)	0.3	2.0	2.3	5.3	4.8	1	-
R(H)	2.1	2.2	2.3	1.8	1.3	1	-
R(D)	1.4	2.1	2.1	1.4	1.4	1	-
R(F)	1.7	2.3	2.7	2.2	1.9	1	-
R(R)	2.0	3.7	4.0	3.3	2.7	1	-

Note. In a column, the values that have a letter in common do not present a significant difference according to the Ficher LSD test at the 5% probability threshold. D% = Proportion of digestate in the substrate; D0% = Control; BA = Aerial biomass; BR = Root biomass; H = Height; D = Stem diameter; F = Number of leaves; R = Number of branches; R (BA) = BA/Control ratio; R (BR) = BR/Control ratio; R (H) = H/Control ratio; R (D) = D/Control ratio; R (F) = F/Control ratio; R (R) = R/Control ratio.

Figure 2. Tomato plants at different digestate proportions

3.3 Assessment of the Microbiological Quality of the Digestate

The results of the microbiological analyses are presented in Figure 3. The total aerobic flora was found to be 4.75E+07 (±3.54E+06) colony-forming units (CFU) per gram of digestate. The indicator bacteria of faecal contamination, namely total and thermotolerant coliforms, were found to be 4.81E+06 (±9.13E+05) and 4.18E+05 (±3.86E+04), respectively. The number of *S. aureus* was 6.14E+04 (±3.21E+03), while the yeast and fungal count was 7.77E+04 (±3.21E+03). The presumed *Salmonella* count was 2.65E+06 (±3.54E+05).

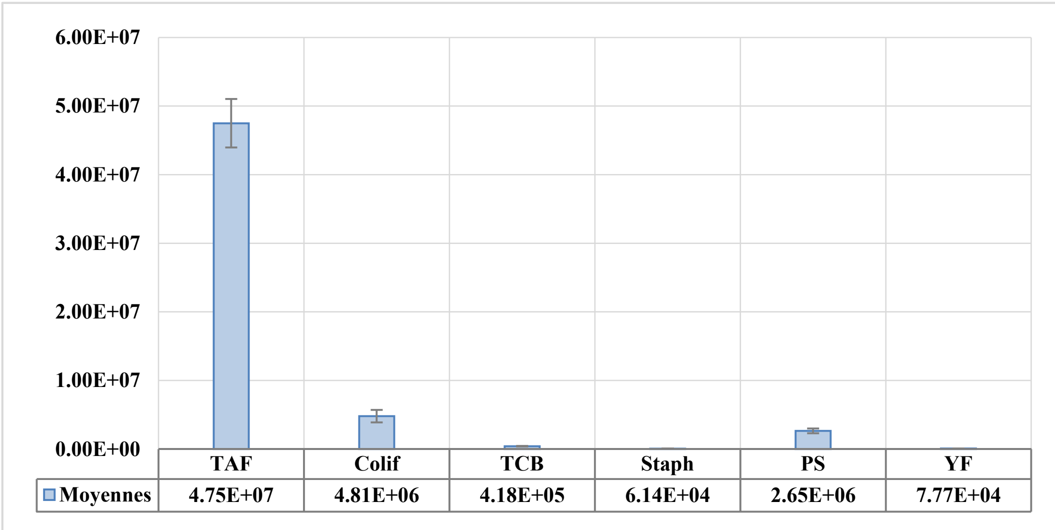

Figure 3. Microorganisms in sludge digestate

Note. TAF: Total Aerobic Flora. Colif: Coliforms. TCB: Thermotolerant coliform bacteria. YF: Yeast and Fungi. PS: Présumés salmonelles. Staph: Staphilocoques.

4. Discussion

4.1 Physicochemical Characteristics of the Digestate

The pH of 8.54 in the digester indicates that the environment is basic. This basicity may be attributed to the degradation of nitrogen compounds, which primarily yield NH_4^+ and NO_3^- ions (Sundberg et al., 2004). As proposed by M'Sadak et al. (2016), pH can be utilized as an indicator of the complete maturation of a substrate. The pH of mature compost is typically within the range of 7 to 8, or even 7 to 9 (Larbi, 2006; Bernal et al., 2009). The presence of highly alkaline conditions can have a detrimental impact on plant life, as pH exerts a significant influence on the availability of nutrients and the potential for toxicity (Cottes, 2019; Bhattarai et al., 2015). The direct application of this digestate without prior treatment could result in an imbalance of the soil's pH, which may impair the ability of plants to absorb available nutrients. Similarly, Soumaré et al. (2002) have indicated that an electrical conductivity of less than 3 mS/cm is optimal for growing substrates. Conductivity levels in excess of the aforementioned threshold may exert a deleterious influence on the processes of germination and seed emergence. A high conductivity value is indicative of a high concentration of ions in solution, which has the potential to impede the uptake of water and nutrients, and may also cause damage to root systems. A positive correlation exists between conductivity and salinity. High conductivity is indicative of high salinity, which can exert two distinct effects during the germination phase: an osmotic effect that is reversible in nature and a toxic effect that is irreversible (Benidire et al., 2015). Additionally, salinity significantly affects the size and density of root hairs.

The organic matter (OM) content is of fundamental importance for soil fertility, given its significant impact on the physical, chemical and biological properties of the soil. The OM content of 83.31% was found to be in accordance with the NF U 44-051 standard (AFNOR, 2002), which specifies a minimum of 30% OM relative to dry matter. Muller et al. (2013) and Maynaud et al. (2017) reported organic matter levels in digestate ranging from 28.6% to 76.5% and 70.4% to 86.3%, respectively. The observed variability can be attributed to the differing compositions of the substrates processed in the digester. The observed variability can be attributed to the differing compositions of the substrates processed in the digester. The variability is due to the differing compositions of substrates processed in the digester. The high organic matter content is beneficial for soil amendment, as noted by Pouya et al. (2021). When applied to the field, such digestate contributes to humification and aids in combating soil erosion, thereby enhancing soil fertility and reducing the impact of erosion, making it a valuable amendment for arid regions like Burkina Faso (Sawadogo et al., 2021). Total organic carbon relative to dry matter was found to 489.8 gC/Kg MS. Maynaud et al. (2017) observed carbon contents ranging from 367.2 to 499.5 gC/Kg MS in both raw and post-treated digestates intended for agricultural use. As carbon is a vital nutrient for microorganisms this amendment would promote biological activity and improve soil porosity according to Sawadogo et al. (2021).

4.2 Agronomic Value of Digestate

The NPK mineral parameters provide information on the digestate's potential to enrich agricultural soil with nutrients (Sawadogo et al., 2021). The values obtained were 50.48 g/Kg MS for nitrogen 0.02 g/Kg MS for phosphorus and 4.72 g/Kg MS for potassium. Muller et al. (2013) reported a variation in total nitrogen (N) contents in sludge digestates ranging from 4.34 to 219.00 g/Kg DM across the 44 studied sites. Maynaud et al. (2017) found potassium (K) contents between 3.2 and 49.0 g/Kg DM in digestates derived mainly from agricultural waste, urban sludge, household waste and biowaste. These potassium (K) contents are higher than those reported by Muller et al. (2013), who found an average of 4.29 g/Kg DM in sewage digestate. The NPK values align the spreading standard recommended by AFNOR (2002), which stipulate those nutrient contents must be below 3%.

The soluble mineral elements contents were as follows: 1.97 g/kg DM for ammonium, 45.99 g/kg DM for nitrate, 0.02 g/kg DM for nitrite, 0.35 g/kg DM for phosphate and 5.90 g/kg DM for sulfate. The high nitrate (NO_3^-) contents limit ammonia volatilization during storage and represent a form directly usable by plants, offering a valuable resource for plant nutrition (Bodson & Vandenberghe, 2013; Dabert et al., 2015). While nitrite is present in small quantities and is not directly usable by plants. It can be converted into nitrate by micro-organisms (Abeliovich, 2006). The $P_2O_5^-$ content (0.35 g/Kg MS equivalent to 0.138% MS) complied with NF U 44-051 standard (AFNOR, 2002) which recommends contents remain below 3%. Muller et al. (2013) found $P_2O_5^-$ contents ranging from 0.55 to 36.60 g/Kg DM across various sludge digestate production sites. This variation can be attributed to the quality of the incoming organic waste and the pre-treatments or post-treatments used. The ammonium contents of 1.97 g/Kg DM is consistent with the values reported by Muller et al. (2013).

4.3 Assessment of Digestate Maturity and Stability

The CO_2 emissions value was 5.26 g/Kg MS/d or 0.22 g/Kg MS/h. The nitrate to ammonium ratio is 23.34 (g/Kg·g/Kg^{-1}) and the determined degree of humification is 0.99. According to Adani et al. (1995) immature sludge has CO_2 emission values of 2.8 g CO_2/kg MO/h while mature sludge has emission values of 1.2 g CO_2/kg MO/h. The emissions are due to a degradation activity of biodegradable products that could not be degraded during methanization. The microbial species thus emerging from their dormancy after a water supply have found energy sources for this purpose in favorable pH conditions (Sawadogo et al., 2021; Konfe et al., 2019). This value is consistent with the value recommended by standard NF U 44-051 (AFNOR, 2002) which recommends a value greater than 8. This value remains lower than that of dehydrated sewage sludge (DSS) which is 18.99 (Sore et al., 2021). This difference reflects the breakdown of organic matter during anaerobic digestion. The C/N ratio is an indicator of the humic potential of conventional organic residues (plant residues and animal waste). *i.e.*, the proportion of stable humus that forms in the soil after decomposition of organic matter. According to Jiménez and Garcia (1989) found a C/N ratio less than 15 indicates mature compost. Aoun and Bouaoun (2006) also reported that a C/N ratio of less than 20 indicates a "mature" digestate. Studies have shown that the higher the C/N ratio of a product, the slower it degrades in the soil and the more stable humus it provides (Robin, 1997). The NO_3/NH_4 ratio was 23.34 (g/Kg·g/Kg^{-1}). Sánchez-Monedero et al. (2001) indicates that a mature compost should have the NO_3/NH_4 ratio greater than 6.3 (g/Kg·g/Kg^{-1}). The degree of humification determined is 0.99. According to Ofosu-budu et al. (2010), the humification degree lower than 0.7 indicates a mature compost. The humification degree obtained is higher than 0.7 therefore the digestate is considered immature. Guilayn et al. (2017) showed the amendment and fertilizing effects of solid and raw digestates on corn. But there is a great divergence of opinion on the maturity and stability of substrates intended for amendment. Abdullah et al. (2016) in a study showed that the stability of digestate depends on the time spent in the digester. Those having spent a very short time of 3 to 15 days are phytotoxic while digestates having spent 70 days are not toxic.

4.4 Study of the Effect of Digestate on Tomato Plants

The results of the germination test of two crops, tomato and cabbage are presented in Table 3. These results show that the digestate has a more sensitive effect on the germination of cabbage seeds (89%) than tomato seeds (100%). Doublet et al. (2004) found a corn germination rate of 96% in municipal waste digestate filtrate compared to 68% in anaerobic compost. The effects on germination could be explained by the presence of ions at high concentrations in the digestate filtrate. Thus, indicating high conductivity values. Indeed, the ions can be Na^+, Cl^-, Cu_2^+, Zn_2^+, Ca_2^+, NH_4^+, NO_3^-, NO_2^- which would increase the concentration of the external environment preventing the entry of water into the seed. This osmosis phenomenon delays or inhibits germination through seed dehydration. The germination index varies depending on the crop and was 137.58 and 82.10 for tomato and cabbage respectively. Pouya (2014) found a corn germination index (63%) for jatropha compost. Sore et al. (2021) found a germination index (GI) of okra (*Abelmoschus esculentus*) of 49.79% and 159.49% respectively for co-composts of proportions 2/1 and 3/1 of sewage sludge and household waste. According to Zucconi et al. (1981), compost is considered non-toxic when its GI exceeds 50%. The germination index of the sewage sludge digestate is greater than 50%. The carbon concentration of 20 g/100 mL or approximately 5 t/ha to 6 t/ha as a field application dose assuming a rooting depth of 15-20 cm was applied. The roots elongated much in the digestate than in distilled water for tomatoes (137.58%). This rate is 92.25% for cabbage. This shows that tomatoes root better in the digestate than cabbage. According to Radhouane (2008) a slight water deficiency improves the length of the radicle in all ecotypes (15.8%). On the other hand, severe water stress reduces it by more than 88% according to Hegarty and Ross (1978). This reduction would be due to a stoppage of cell division and elongation at the root level, leading to a sort of "tuberization" according to Fraser et al. (1990). The tuberization and lignification of the root system allow the plant a slowed "entry into life" while waiting for conditions to become favorable again.

The results of the tomato emergence and leaf growth test showed that sewage sludge digestate can be a good tomato growing medium at concentrations ranging from 25 to 75% with 50% as the ideal proportion. Proportions lower than 25%, the nutrient supply will be insufficient which would have repercussions on the development of the plant. Beyond 75%, growth anomalies appear, stunting, quivering, leaf color, gnawed roots. From 25 to 75% digestate the plants appear to flourish with uniform morphological characteristics in the three pots. Mouria et al. (2010) found growth anomalies with the proportions of 100% digestate, this could be due to the toxic effect of digestate often due to high salinity. Indeed, the high salt content affects the growth of plants which can result in root and foliage burns (M'Sadak et al., 2012).

4.5 Evaluation of the Microbiological Quality of the Digestate

The digestate was found to contain a diverse range of microorganisms, including total aerobic flora and yeasts and molds. In order to ascertain the presence of faecal contamination, indicator microorganisms, specifically total and thermotolerant coliforms, were also enumerated. Additionally, the presumed pathogens S. aureus and salmonella were identified within the digestate. Miguel et al. (2020) found 2.4×10^7 CFU g^{-1} of total flora, 2.5×10^6 CFU g^{-1} of total coliforms, and 6.3×10^5 CFU g^{-1} of S. aureus with a total absence of *Salmonella* sp. Our results were slightly higher than those of Miguel et al. (2020) excepted for *S. aureus*. Bonetta et al. (2014) found a Mesophilic bacterial counts of 5.3 log10 CFU g^{-1} equivalent to 1.99×10^6 in digestate from Anaerobic Co-Digestion of Organic Waste. According to Rashid et al. (2016), bacterial and fungal microorganisms have the potential to restore the fertility of degraded lands through various processes. Indeed, microorganisms enhance the bioavailability of nutrients through processes such as nitrogen fixation and the mobilization of essential nutrients, including phosphorus, potassium, and minerals, which are crucial for optimal crop growth. Additionally, they facilitate the remediation of soil structure by improving its aggregation and stability. The assessment of soil fertility is based on the analysis of soil microbial biomass, diversity and activities, which serve as key indicators in this process (Petitjean et al., 2019). The presence of microorganisms in soil can also be indicative of soil quality. The soil can be more or less affected by pathogenic microorganisms from sources of amendments such as compost, animal excrement, and digestate. The presence of coliforms indicates a felt faecal contamination, which can be attributed to the sludge's origin as waste water and excreta. The species most frequently associated with this bacterial group is *Escherichia coli*. According to Edberg et al. (2003), *Escherichia coli* bacteria represent 80-90% of the thermotolerant coliforms detected and, as a result, may constitute a public health risk. Pathogens such as *Salmonella* sp. and Staphylococcus aureus were counted in the digestate with respective loads of 2.6×10^6 and 6.18×104 CFU g^{-1}. The study conducted by Bonetta et al. (2014) revealed the presence of Salmonella sp. in 100% of the digestate samples. The presence of Salmonella in the digestate samples may indicate a hygiene issue. The absence of Salmonella in 25 g of material is an indicator of the absence of bacterial pathogens and is considered the standard for the use of digestate as a field amendment.

5. Conclusion

The objective of this study was to assess the agronomic characteristics, effects on seeds, growth of tomato plants and potential microbiological risks of digestate produced at the Kossodo feacal sludge treatment and recovery plant in Burkina Faso. The results of the physicochemical analyses indicate that the raw digestate is basic with a high electrical conductivity value. The total nutrient content was 50.48 N, 0.02 P and 4.72 K. The soluble compounds were 1.97 g, 45.99 g, 0.02 g and 0.35 g. Digestate has agricultural potential, but it is not fully mature, which could affect how plants grow. The seeds germinated at a rate of 137.58% for tomato seeds and 82.10% for cabbage seeds. Furthermore, the presence of specific pathogenic microorganisms in the digestate samples gives rise to concerns regarding hygiene. There's a risk that using this material in agriculture could lead to public health issues because it could spread pathogens. While the digestate resulting from anaerobic digestion of sludge undoubtedly possesses agronomic potential, it must undergo further treatment prior to any potential application.

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Authors Contributions

Sample: Dr. NM and HN were responsible for study design and drafted the manuscript. Dr. ASO and Dr. COTC were responsible for data analysis. Dr. KSM, Pr. GKOB and Pr. ASO revised it. All authors read and approved the final manuscript. In this paragraph, also explain any special agreements concerning authorship, such as if authors contributed equally to the study.

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Data Sharing Statement

No additional data are available.