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ISSN (Print: 2357-0849, online: 2357-0857)

Environmental Science and Sustainable Development

Research Paper

Received:19 August 2025, Accepted: 28 December 2025, Published online: 31 December 2025

DOI: 10.21625/essd.v10i4.1234

Sustainable plant nutrients generated from symbiotic waste treatment for safe application in food crop production

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Abstract

Adequate soil nutrients are necessary for plant growth and health. Nitrogen sources from synthetic ammonia production have a high energy requirement, with implications for global warming. Innovative ways of producing nitrogen, such as crop nutrients from municipal organic waste, have significance on materials circularity and the achievement of a number of sustainable development goals. The feasibility of transforming potentially hazardous waste into plant nutrients is explored. The physiological response of tomato crops cultivated with the as-produced nitrogen source in a completely randomized design pilot field trial to evaluate the quality and health risk associated with the recycling of potentially hazardous waste into nutrient sources for food cultivation is reported. The recycled solid nutrient source can support the cultivation of tomatoes with plant physiological responses comparable to the same nitrogen levels application of artificial fertilizer. The risk associated with heavy metals and pathogen contamination of food is also limited.

Keywords

Plant nutrients; anaerobic digestate; organic fertilizer; waste management; circular economy; heavy metals uptake

1. Introduction

Adequate nitrogen content in soil is necessary for the production of chlorophyll in plants, a requisite for plant growth and health. The conventional method (the Haber-Bosch process) of producing ammonia as a source of nitrogen, a primary nutrient, is an energy-intensive activity with an estimated 37.4 GJ/tonnes of ammonia produced (Erisman et al., 2008). This makes it a major contributor to greenhouse gas emissions, releasing approximately 1909 kg of CO_2 per tonne of ammonia produced using natural gas and about 5450 kg of CO_2 per tonne when produced using grid electricity. It is therefore important to adopt innovative and eco-friendly methods of restoring the nutrient content in soil.

Water used for sanitation translates into huge volumes (averaging *ca* 41,000 litres/person/annum). This water also contains nutrients that can be harnessed to support food production using eco-innovative technologies, thereby ensuring a sustainable circular water economy. It is still common practice to apply untreated sewage directly to farmlands as manure in communities where chemical fertilizers are expensive and government-subsidized options are inaccessible (Antwi-Agyei et al, 2016). The health hazards associated with a high potential of contaminating food with pathogens and helminths are usually not considered. Inappropriate disposal of liquid waste, particularly sewage, continues to be a major challenge to the attainment of the Sustainable Development Goals in most developing countries.

Anaerobic digestion is a valuable tool that synchronizes a series of enzymatic reactions to break complex food like carbohydrates, fats, and proteins, including pathogens, in a carefully controlled environment of pH and temperature and the absence of oxygen to produce biogas (CH_4 and CO_2) and a nutrient-rich slurry (digestate) (Bayitse et al., 2014). In the first stage of the reaction, extracellular enzymes like cellulase, amylase, protease, and lipase hydrolyse long-chain complex food compounds, decomposing them into simpler molecules (simple sugars, amino acids, and fatty acids). Acidogenic bacteria then convert the intermediary products into smaller molecular weight molecules (acetic acid, alcohols, H_2, and CO_2), which in the last phase are converted to CH_4 by methanogens (Manchala et al, 2017). Different temperature regimes for the operation of the digester determine the inoculum type to be used and the required retention time for complete digestion of substrates. Mesophilic digestion has a temperature range of 20-45 °C whilst thermophilic reactions require temperatures between 50 and 70 °C (Gebreeyessus & Jenicek, 2016). The co-digestion of food waste with sewage affords a green technology of producing safe nutrients that can be exploited for "fertigation" (application of nutrients and water), where the volume of water discharged as part of the effluent is high or as solid plant nutrients when dried.

Municipal Solid Waste (MSW) incineration is a viable waste disposal method for reducing the bulk volume of waste disposed of in landfills, thus extending the lifetime of the landfills. The challenge with the use of incineration has been the potential of releasing harmful gases and solid residual ash into the environment. However, a combination of interventions, including source segregation of waste, incineration at high temperatures whilst ensuring high retention time of flue gases (Akufo-Kumi et al., 2014), as well as the valorization of the residual ash, can reduce the environmental impact of incineration and make it a preferred waste disposal technique. Innovative ways of producing crop nutrients from locally available resources enhance food security, reducing hunger (SDG 2) as well as increasing productivity and reducing poverty (SDG 1). It also supports good health and well-being (SDG 3) through improved sanitation (SDG 6), particularly among small-holder farmers who produce the bulk of food in most developing countries and yet are amongst the poorest. Thus, with innovative technologies, resources can be redefined to include waste, enabling the achievement of SDG 12, sustainable production and consumption (Figure 1).

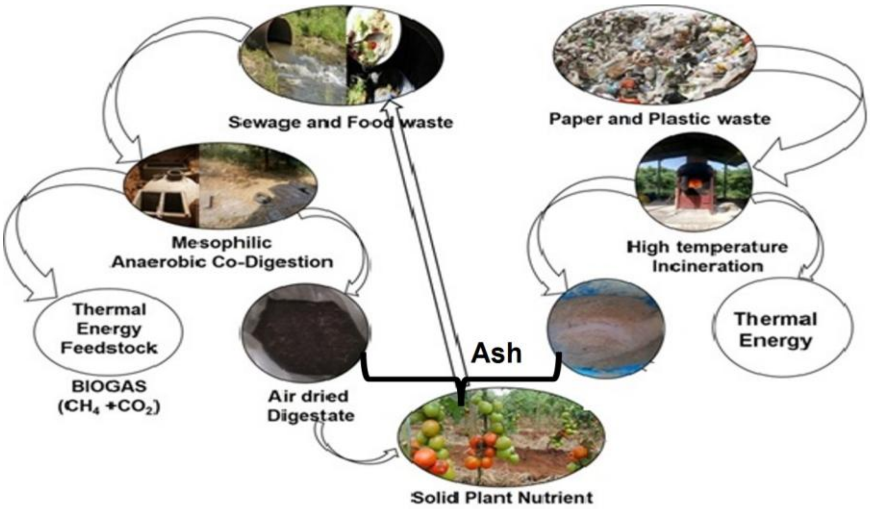

Figure 1: A schematic representation of the materials cycle in the eco-innovative waste-to-nutrient nexus (source: by authors)

This paper aims to evaluate the quality (ensuring optimal plant growth) and assess the health risk (exposure to pathogens and heavy metals) in using potentially hazardous waste like human faecal matter and MSW incinerator ash to produce solid plant nutrients for the cultivation of tomato (Solanum lycopersicum) crop in a circular materials economy.

2. Materials and Methods

2.1 Materials

Solid inorganic NPK fertilizer (artificial fertilizer) was bought from the open market and used without any further treatment. Solid digestate (Safisana) was obtained from a batch of a commercially operated mesophilic anaerobic biodigester in Ghana, which produces biogas from the co-digestion of faecal matter and food waste for the generation of electricity. Pectomec variety of the tomato (Solanum lycopersicum) seeds, common in Ghana, was purchased and used for the study. The seeds were nursed in trays at the CSIR-IIR.

2.1.1 Preparation of ash-treated solid digestate from CSIR (Ash)

The CSIR Solid digestate was obtained by sun drying the slurry of the effluent from the mesophilic anaerobic baffled digester system for treating faecal matter and biodegradable waste from CSIR-Institute of Industrial Research (CSIR-IIR). The dried sample was weighed and stored in a labelled polythene bag in a dry environment. Incinerator ash (particle size less than 650 microns) was collected by sieving the residue of combustion material from an on-site solid waste incinerator with a destruction efficiency of about 90% for disposing of municipal solid waste (MSW) from the CSIR-IIR at operating temperatures above 850 ^{o}C. An ash-treated solid digestate (SDA) was prepared by uniformly mixing 80 parts of solid digestate with 20 parts of incineration ash. The homogeneous mix (labelled SDA) was weighed and stored in a labelled polythene bag in a dry environment.

2.2 Methods

2.2.1. Sampling of liquid digestate (LD)

Three grab samples (1 L) of liquid effluent from the settling tank of the CSIR-IIR anaerobic digester were collected (at monthly intervals) at 7 am before the facility opens for business into a clean, dry polyethylene terephthalate (PET) bottle and stored at 4 ^{o}C to minimize chemical and microbial changes. The settling tank effluent holds the characteristic clarified supernatant formed after the solids have been separated in the digestion process. The liquid digestate, therefore, contains the nutrients present in the liquid fraction. The sample was then transported to the laboratory for analysis. All analyses were performed in triplicate to ensure repeatability and reliability of measurements.

2.2.2 Physico-chemical analysis

The pH of the samples was obtained by the electrometric method. This was done by preparing a slurry with 10.0 g of the solid sample and 10 ml of deionized water and then mixing thoroughly for an hour. The pH electrode (VWR model) was immersed in the slurry to establish an equilibrium between the electrode and the sample, and the readings were recorded. The pH of the liquid digestate was obtained by immersing the pH electrode in the liquid sample and stirring gently to allow an equilibrium to be established and recorded. Similarly, the electrical conductivities of the solid and liquid samples were obtained using an electrical conductivity meter (VWR model) following the same protocol.

2.2.3 Nutrient analysis

Total nitrogen content of both the solid and liquid samples was determined using the Kjeldahl method (APHA, 1998).

The elemental analysis of the powdered samples was determined by the hazardous waste test methods SW-846 test method 6200 (EPA, 2007) using an Oxford Twin X, X-ray Fluorescence (XRF) spectrometer. XRF has been used as a non-destructive technique to monitor the concentration of elements from Na to U with a limit of detection of 1.0 mg/kg (Almeida & Cunha, 2025) (Byers et al, 2019).

2.2.4. Microbial analysis

The Total coliform (TC) in the sample was determined using the membrane filter technique APHA 9222A (APHA, 1998).

The faecal coliform was determined using the membrane filter procedure in the standard method APHA 9222D (APHA, 1998).

The pathogenic *Escherichia coli* (*E. coli*) in the sample was determined using the conventional biochemical testing as described in the standard method APHA 9260 F (APHA, 1998).

The Helminth eggs in the sample were determined using the Ammonium bicarbonate/ zinc sulphate standard method for detection of helminth ova, WRC (S.A.) TT 322/08 (WRC, 2008).

2.2.5. Determination of chlorophyll content in the apical leaf

Chlorophyll content in the apical leaves of the tomato plants was monitored by a non-destructive method using a portable chlorophyll meter (Apogee MC-100). The values were recorded in µmol of chlorophyll per m^2 of leaf surface.

2.2.6. Field Experiment Design

A field trial was established on a 0.5-acre plot of coastal savanna parcel of land at the CSIR-IIR in Accra, Ghana (Latitude 5.65868, Longitude - 0.1483) to evaluate the feasibility |of using potentially hazardous materials as a raw material for the production of crop nutrients and their impact on the quality and health risk of the food crops so produced. The experimental design adopted for the field trial was a Completely Randomized Block Design (CRBD) with three replications (see Figure 2). The different application of different sources of nitrogen and the control is indicated by the different hues of colour in Figure 2. In all, there were 15 plots with each plot having a dimension of 2 m x 4 m and an inter-plot spacing of 1.5 m. The experiment was conducted in the dry season, with the source of water coming only from a drip irrigation system with water from a borehole.

The soil of the field experiment was conditioned with the equivalent of 90 kg of N per hectare for the nutrient sources NPK (artificial fertilizer), Solid digestate (Safisana), and the ash-treated solid digestate (SDA), a month before transplanting. The portion for the controlled experiment was not treated with any nitrogen source. The tomato seedlings were transplanted when they were four weeks old, with 24 plants per plot. The plot for Liquid digestate treatment was not cultivated because the amount of nutrients in the liquid digestate was too low to support the nutrient needs of the tomato crop in reasonable applications. The second Nitrogen application of 90 kg of N per hectare was done on the fourth week after transplanting. The remaining nitrogen was to be supplied in equal portions at intervals to reach the 340 kg of Nitrogen per hectare at the point of fruit bearing. The data on apical leaf chlorophyll were monitored weekly for 12 weeks.

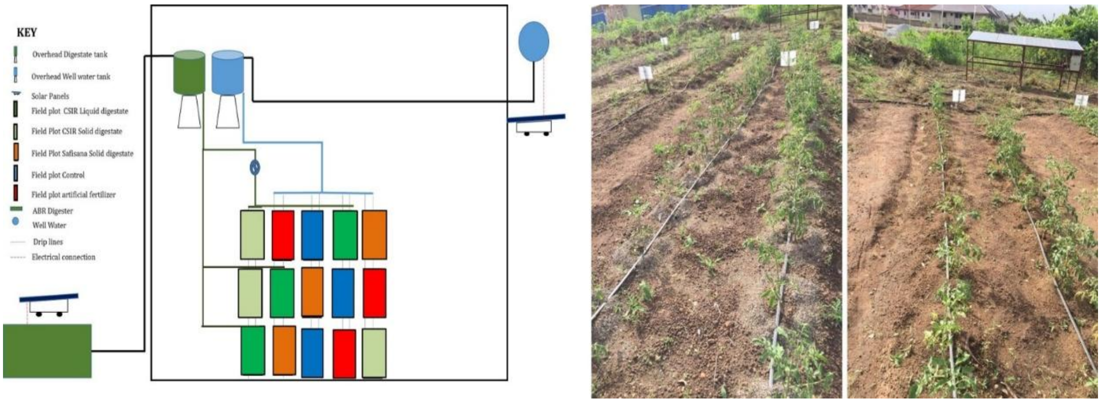

Figure 2: The schematic design (left) and field experiment (right) set-up of the drip irrigated tomato plants in completely randomized demarcated rows. (source: by authors)

3. Results

3.1 Quality assessment of digestate as a nutrient source

To avert the potential risk of introducing pathogens during irrigation (Hong & Moorman, 2005) or uptake of pathogens by plants from soils contaminated by poorly treated wastewater (Oluwadara et al, 2018) in the nutrient application, the microbial content of the digestates was assessed. Total coliform bacteria are a group of microorganisms found in the environment, and their presence may be indicative of the presence of harmful pathogens (Medeiros et al., 2024). Faecal coliforms are the thermotolerant subset of total coliforms and *E. coli* of faecal origin and constitute more than 95% of the coliform genera in human faeces. Therefore, it is suggested in literature that measuring *E. coli* in effluents is the most useful indicator in assessing the efficiency of a treatment process, providing greater public health protection (Elmund et al, 1999). Microbial activity also influences the quality of the fertilizer (Martin-Sanz-Garrido et al, 2025). The results, as shown in Table 1, indicated about 97% reduction in common pathogens such as faecal coliform after anaerobic digestion and further reduction in pathogens after modifying the solid digestate with incinerator ash (ca 42% CaO) to 99.9%. The CaO reacts with water to produce $Ca(OH)_2$, which has been known to have antibacterial activity because of its destructive effect on bacterial cell membranes and protein structures (Siqueira Jr, 1996). Treating digestate with 20% wt/wt. Incinerator ash gives a pH regime of a solid nutrient 8.83±0.08, which inhibits acidophilic and neutrophilic bacteria, including *E. coli*, successfully reducing the risk associated with contamination of fresh produce from nutrient application. The helminth eggs (*Strongyloides stercoralis*) were found in the untreated sewage at the inlet of the digester (6 helminth eggs/L). This presents a major health hazard and therefore necessitates treatment to prevent recontamination. No helminth eggs were observed in the liquid digestate, which suggests that the treatment was effective in the removal of S. stercoralis. 2 helminth eggs/L of *S. stercoralis* were found in the solid digestate initially. The population was, however, halved (1 helminth eggs/L) as a result of treatment with the incinerator ash. Earlier work by Saqer et al (2007) suggested that storing wastewater for more than 17 days or a pH modification of wastewater to high alkalinity levels (pH 10.2) can inactivate the larvae of *S. stercoralis*. The prevalence of *S. stercoralis* as a soil-transmitted helminth contamination makes further treatment by storage for longer than 17 days after formulation a prerequisite, and also the necessary precautions need to be observed during application in order not to activate an autoinfection cycle (White et al, 2019).

Table 1: Pathogen analysis in the different organic nutrient sources (source: by authors).

	Types of Digestate							
Microorganism	Safisana SD $x10^5$	CSIR LD Inlet $x10^5$	CSIR LD Outlet $x10^5$	CSIR SD $x10^5$	CSIR SDA treated $x10^3$	Pathogen kills off in LD %	Pathogen kills off in SD. %	Pathogen kill off in SDA. %
Faecal coliform (cfu/100 ml)	1	128	4	4	4	96.9	96.9	99.9
E. Coli (cfu/100 ml)	-	8	-	2	-	100	75	100
Total Coliform (cfu/100 ml)	9	216	8	19	68	91.2	96.3	99.7

Plants generally require about 17 essential elements for growth and development (Brown et al, 2022). Three elements comprising, carbon, hydrogen, and oxygen, are often extracted from the atmosphere and soil water by the plant. However, the remaining 14 (nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, iron, zinc, manganese, copper, boron, molybdenum, chlorine, and nickel) are derived from sequestration from soil minerals and organic matter in the soil (Brown et al, 2022). The quality of the digestate as a nutrient source was thus assessed by the concentrations of essential nutrients, N, K, and P, as well as levels of secondary level micronutrients such as Ca, which improves the sellable part of the plant. The primary nutrients in the liquid digestate (supernatant liquid effluent) from the CSIR-IIR anaerobic digester show very low concentrations of N, P, and K (Table 2). This is because one of the major features of mesophilic anaerobic digester designs is the discharge of effluents with low nutrient levels (Gebreeyessus & Jenicek, 2016) to prevent eutrophication, which can cause algae bloom. Hence, a settling tank feature ensures the entrapment of slurry (solid digestate), which has richer nutrient concentrations. A comparison of the nutrient levels of a solid digestate produced in the two mesophilic anaerobic digester systems shows that N and K levels of the digestate from the commercially operated digester (Safisana) were higher than those from the CSIR solid digestate (SD), whilst CSIR SD had higher levels of P. This could be typical of the raw material, substrate, fed into the digester. This confirms that co-digestion of waste whilst boosting biogas production (Bayitse et al., 2014) can also improve the nutrient quality of the digestate for agricultural purposes. Also, the fortification of the digestate with CaO from the incinerator ash can increase N (NO_3^-), K, and P absorption from the soil as well as increase the size of sellable plant parts. The addition of nutrients from the treatment of organic waste has long-term benefits to soil health, as the humic matter helps in the retention of moisture and also prevents easy leaching of nutrients from the soil during rain runoffs. The materials' circularity also has long-term benefits to the global environment.

Table 2: Comparison of the nutrient levels of the different fertilizers used (source: by authors)

Parameter	Nutrient Source					
	Artificial fert.	Safisana SD	CSIR LD	CSIR SD	SDA	Incinerator Ash
pH	ND	7.0	7.13	7.35	8.83	11.84
Electrical Conductivity (µS/cm)	ND	3959	4,430	517	4640	7490
Total P (mg/kg)	100,000	11,204	1.77	15,505	16,254	235
Total N (mg/kg)	230,000	28,775	11.7	14,280	13,902	11,760
Ca (mg/kg)	20,000	16,764	-	50,505	130,480	419,400
Mg (mg/kg)	-	4,263	-	-	2,517	11,524
K (mg/kg)	50,000	10,678	83	4,228	6,111	7,046

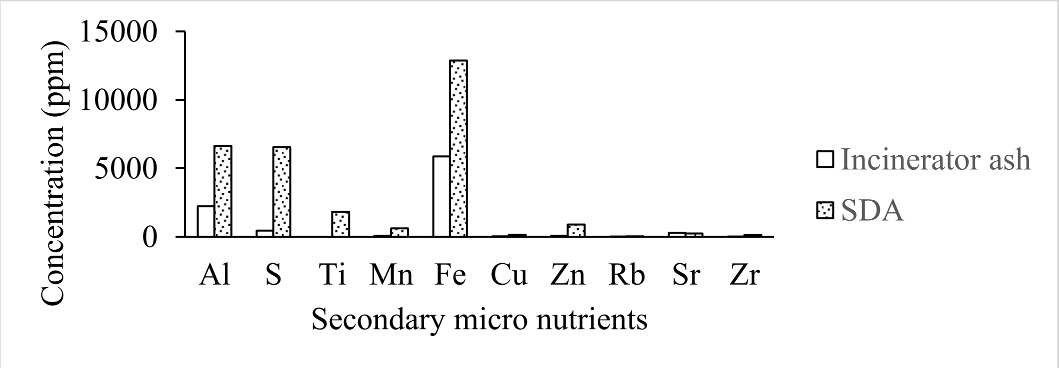

Figure 3: Levels of some essential metals in the incinerator ash and the ash-treated CSIR solid digestate (SDA) as determined by XRF (source: by authors)

Toxic heavy metals (Pb, Hg, As, Cd) that could bioaccumulate with hazardous human health consequences were below the detection limit of the X-ray Fluorescence (XRF) spectrometer. This shows that segregation is an important process in waste treatment in order to valorize waste without exposure to greater health risks. The presence of other micronutrients like Cu, Fe, Zn, and S in the solid nutrient (Figure 3) could help in plant growth and development. However, there were also traces of Mn and Al, which have been shown to have toxicity to plants (Brown et al, 2022).

3.2 Field testing of formulated solid nutrients

The physiological responses and crop yield for the various nutrients used in the field trial were assessed to determine whether the source of nitrogen had any significant effect on plant growth and fruit development. The data was analyzed using the Student's t-test for unpaired variance. A p-value less than $\alpha=0.05$ was considered statistically different. Figure 4 and Figure 5 show the response of the tomato plant to the different treatment sources administered at the same nitrogen content, with the control experiment having no nitrogen treatment. The results are represented as mean ± SD for 3 replicate plots with different alphabets indicating a significant statistical difference with p-value $< \alpha$ (0.05).

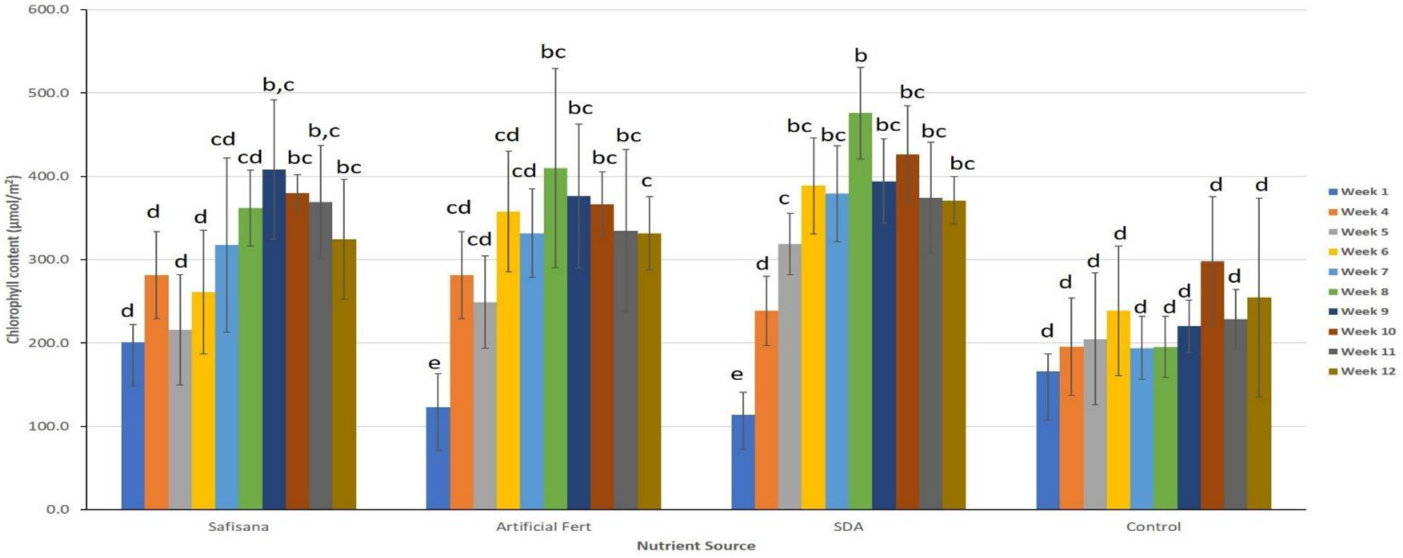

Figure 4: Monitoring of chlorophyll content (µmol/m^2) in the apical leaves of tomatoes in the field experiment for 12 weeks after transplanting. (Source: by authors)

The chlorophyll content of the apical leaves on the apical meristem, responsible for primary growth, is indicative of absorption of nitrogen from the soil (Goncalves et al, 2020). The results (Figure 4) depict that in Week 1, the absorption of nitrogen from the soil in the control plot was significantly higher than the SDA (p=0.0129) and the artificial fertilizer (p=0.0084), though similar to the Safisana treatment plot (p=0.1091). Though both SDA and Safisana plots were treated a month before transplant, the chlorophyll content in the Safisana-treated plants was significantly higher than that of the SDA (p =0.0049). After Week 4, the plants responded very well to the uptake of the nitrogen application; thus, there was no significant difference in the chlorophyll content of the apical leaves in plants on all the experimental plots (Figure 4). However, after Week 5, the chlorophyll content in the apical leaves of SDA-treated plants becomes significantly higher than the control (p=0.0037). The nitrogen absorbed by the plants in the control experiment begins to lag behind the other treated plots by week 8 to week 12. A similar trend has been observed in the literature, attributing increased nitrogen requirement for the flowering stage of the plant for the synthesis of essential biomolecules (Zhao et al, 2025). This indicates that the tomato plant responded very well to the nitrogen application. The increase in chlorophyll content for the Artificial Fert and Ash treatment was 63% and 70%, respectively, higher than that of the control experiment, suggesting that the nitrogen source released the nutrients readily.

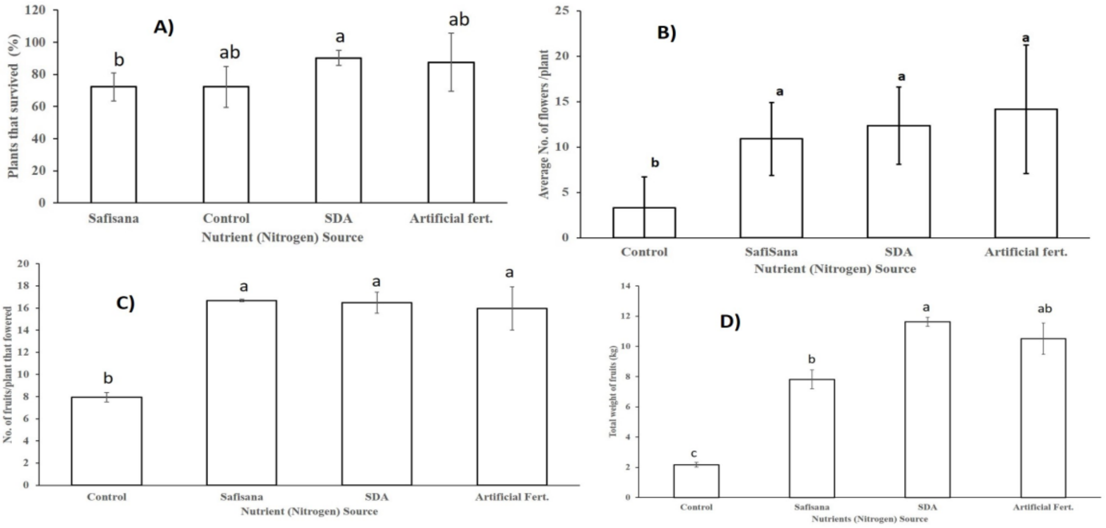

Figure 5: Physiological responses and crop yield of the tomato plants to various nitrogen source treatments. A) The percentage of plants that survived, B) Average number of flowers/plant, C) Number of fruits/flowered plant, and D) Total weight of fruits/nutrient treatment. (Source: by authors)

Physiological responses and crop yield of the tomato plants were studied, and the results are reported in Figure 5, showing averages ± standard deviation of 3 replicate plots with different alphabets indicating a significant statistical difference with p-value < α (0.05). The use of NPK biofertilizers and biostimulants can significantly influence seed germination, seedling survival, and mortality rates (BharathKumar et al., 2025). Solid humic substances have also been reported to be beneficial in enhancing transplant quality and post-transplant yield performance (Qin & Leskovar, 2020). The different nitrogen nutrient sources may have different concentrations of humic substances because of the different starting materials and their process methods. Thus, the survival rate of the plants in the field trials is evaluated. The survival rate of the transplanted seedlings in the artificial fertilizer application was not significantly different from SDA and the control (see Figure 5A). The SDA treatment, however, had about 18% increase in survival rate compared to the untreated solid digestate (Safisana) treatment plots (p-value = 0.0243). There was no significant difference between the survival rate in the Safisana treatment plot and the control (p-value = 0.4986). This shows that the plants adapted well to the SDA nutrient source and that the form of the nitrogen source did not negatively impact the plant survival.

Flowers and fruits have a close correlation in flowering plants like tomatoes. The number of flowers on a plant is an indication of the fruiting probability of the plant. It is reported that taller plants, which tend to have longer inflorescences and more flowers, produce more fruits (Taura & Zigmantas, 2024). Though nitrogen is essential for this step of the plant development, the type of nitrogen nutrient has been reported to impact both on the quality and quantity of the yield. An optimum balance in nitrogen in the form of nitrates and ammonium is therefore required (Wang et al., 2024). The results depicted in (Figure 5B) show that whilst there is no significant difference between the three different nitrogen sources, all the treatment methods performed better than the control experiment SDA (p-value = 0.0239), Safisana (p-value = 0.0.0339), and Artificial fertilizer (p-value = 0.0499). The results confirm the importance of nitrogen as a nutrient in triggering fruit formation and that the nitrogen in the form of SDA is releasable for plant growth and fruit development (Wang et al., 2024).

Though a number of environmental conditions, like inadequate pollination, extreme temperature, and water stress, may cause a tomato to flower but not fruit, the effect of nutrient source on fruit development was investigated. The results in Figure 5C show the number of fruits per flowered plant. There were no significant differences between the different nutrient sources in fruit development, though all the different nutrient sources were significantly higher than the control. 58% more flowers on the plants in the SDA treatment plot developed fruits than the control. This shows clearly that whilst nitrogen is an important nutrient to plant health and its fruiting probability, the source of nitrogen cannot be discriminated clearly in terms of flowering and fruit formation. The quality of the produce in terms of weight of the fruit was assessed (Figure 5D) as it has been reported in the literature to be affected by the type of nitrogen and the ratios of the different nitrogen forms in the nutrient formulation (Wang et al., 2024). The results (Figure 5D) show whilst there was a clear difference between crop yield in the different treatment plots (SDA, Safisana and Artificial fertilizer) and the control, there was a significant difference in the yield (weight of fruits) between SDA and Safisana (p-value = 0.0191) which may be due to the nitrate, ammonium ratio (Wang, et al., 2024). The conversion of ammonium nitrogen (NH_4^+) to nitrate nitrogen (NO_3^-) in the presence of oxygen produces acidity (H^+) as depicted in equation $2NH_4^+ + 4O_2 \rightarrow 2NO_3^- + 4H^+ + 2H_2O$. Thus, the treatment of the digestate with alkaline ash is likely to shift the reaction towards the conversion of ammonium to nitrate, leading to a better nitrate ammonium ratio compared to just the solid digestate (Safisana treatment). The tomato yields in the field trial were estimated as ash-treated digestate, SDA (4.8 tonnes/ha), artificial inorganic fertilizer (4.3 tonnes/ha), untreated solid digestate, Safisana (3.26 tonnes/ha), and the control (0.90 tonnes/ha). Though the yield was significantly lower than the Ghana national average of 7.82 tonnes/ha and the global average of between 40 -50 tonnes per hectare (Food and Agriculture Organization of the United Nations, 2025), the yield was not a result of a nitrogen deficiency and could be optimized with better agronomic practices.

3.3 Metal uptake in the tomato fruit

Analysis on the elemental composition in the fruit formation of a sample of tomatoes harvested from the plants was conducted to examine the level of uptake of heavy metals from the soil because of the health risk it poses through potential bio-concentration and accumulation. The results, as indicated in Table 3, show the presence of Pb (4 mg/kg) in only the fruit from the Artificial Fertilizer-treated plot. Also, the presence of Pb in the soil after application of artificial fertilizer, despite no detection in the soil of the control, as shown in Table 3. The World Health Organization (WHO) and the Food and Agriculture Organization (FAO) permissible limits of Pb in fruits is between 0.01-3.0 mg/kg and 30-50 mg/kg in soil whilst the maximum permissible limits in fruits for As, Cd and Hg are 0.2 mg/kg, 2.0 mg/kg and 1.0 mg/kg respectively (Codex Alimentarius: International Food Standards, 1995 (Revised 2024)). This suggests a possible higher risk of heavy metal contamination during the nitrogen application, which may have led to uptake by the plant, as is seen in the case of the artificial fertilizer treatment plot, than in the other organic fertilizers. This suggests that the XRF with a detection limit of 1.0 mg/kg may be adequately sensitive to evaluate the upper limits of possible contamination of fruits from Pb, Hg, and Cd, but not adequately sensitive for As. From the results, it can be posited that the risk associated with the use of the artificial fertilizer was higher than that of using the ash-amended digestate. This highlights the risk of introducing toxic metals through fertilizer application and hence the need to continuously monitor the levels of these metals in food crops cultivated with nutrients from waste precursors.

Table 3: Elemental composition of soils (post-harvest) and of fruits from the different treatment plots expressed in mg/kg on a dry weight basis compared with permissible limits by [the] International and [b] European Union standards.

Heavy metals	Heavy metals composition (mg/kg) on a dry basis								Permissible limits (mg/kg)	
	SDA		Artificial Fertilizer		Safisana SD		Control		Food	Soil
	soil	Fruit	Soil	Fruit	soil	Fruit	soil	fruit		
Fe	13322	BDL	18421	275	14935	388	2728	96		
Mn	643	BDL	957	BDL	589	BDL	501	BDL		
Zn	48	48	31	56	BDL	35	33	25		
Zr	24	25	416	14	383	12	367	20		
Rb	20	30	17	57	19	26	20	49		
Sr	24	19	24	23	20	20	18	19		
Pb	15	BDL	5	4	BDL	BDL	BDL	BDL	0.01–3.0[a], 0.02-3.0[b]	30-50[a]
Cd	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.05-2.0[a], 0.05-3.0[b]	0.9-3[a]
As	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.1-0.2[a], 0.1-0.2[b]	20.0[a]
Hg	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.5-1.0[a], 0.1-1.0[b]	0.03-2.0[a]

NB [a] represents the International standard, [b] represents the European Union standard, and BDL represents below detection limit.

The results from Table 3 show a slow uptake of heavy metals, particularly Fe, by the tomato plant from the soil when the digestate was treated with incinerator ash (Ash) as compared to the other treatment plots and even the control plot. This could be because of the alkalinity of the soil as a result of the higher pH from the incinerator ash. Thus, confirms earlier observations that alkaline soils reduce the bioavailability of heavy metals compared to acidic soils because the heavy metals tend to be immobilized in high pH soils (Seleiman & Kheir, 2018).

3.4 Comparison with other natural nutrient forms

Since antiquity, the benefits of using ash to improve plant growth have been known. The practice of slash and burn, though harmful, particularly to microorganisms in the soil, remains prevalent in some communities in developing countries. The use of animal droppings as manure as a source of nitrogen and plant-based residue like food scraps, yard trimmings, and crop residues as mulching materials for soil enrichment is also extensively practiced for plant cultivation. However, these have negative implications through the introduction of pathogens (particularly from manure), the release of global warming gases, and the release of offensive odour. Compost fertilizer production from organic waste is thus seen as a sustainable practice for soil amendment, as the aerobic biodegradation largely reduces the odour (Bremaghani, 2024). Nevertheless, there are concerns about contamination with pathogens, particularly when using human excreta (Antwi-Agyei et al, 2016), and also the risk of excessive heavy metals introduction into the soil (Bremaghani, 2024). Though some pathogens (helminths eggs) persisted and can even multiply in anaerobic digester systems as suggested in the literature (Lin, et al., 2022), this study shows that treating the anaerobic digestate derived from faecal wastewater and amending with ash reduces the risk considerably and makes it a viable source of plant nutrient for sustainable agriculture in agreement with the literature (Martin-Sanz-Garrido, 2025). The alkaline-amended digestate, apart from inactivating residual pathogens in potentially hazardous organic waste like human excreta, also reduces the bioavailability of heavy metals in the soil for plant uptake.

4. Conclusions

Anaerobic digestion has been exploited as a tool for the treatment of the organic component of wastewater to produce safe plant nutrients, with about 97% of faecal coliform deactivated. The amendment of the digestate with incinerator ash, which is alkaline, further reduced the faecal coliform by 99.9%. The nutrient levels in the treated wastewater are high enough to support good plant health and fruit yield in a very heavy feeding crop like tomatoes, with crop yields of the SDA (4.8 tonnes/ha) comparable with artificial fertilizer (4.4 tonnes/ha) under similar cultivation conditions. Alkaline treatment of the soil reduces the risk of bioavailability of toxic elements in foods cultivated, but the high pH of the soil from continuous application of the as-produced nutrient can also decrease the availability of phosphorus and micronutrients like Fe, Zn, and Cu due to the alkalinity of the soil. The prospect of producing safe plant nutrients from wastewater is therefore very high, with good agronomic practices and more detailed field trials over a longer period required to confirm its viability as a commercial process. Thus, a symbiotic materials circularity waste treatment process can be exploited in the production of sustainable plant nutrients whilst ensuring long-term soil health. However, there remains a remote threat of contamination of soil-transmitted *Strongyloides stercoralis* even after further amendment of the digestate with the incineration ash, hence requiring long storage periods before application to minimize the risk.

Acknowledgments

Part of this work was presented at the 2019 Eco-Innovation Conference at Lancaster, UK.

Funding declaration

The Research work was undertaken with funding from the Global Challenges Research Fund (GCRF) Recirculate Project (2017-2020)

Ethics approval

Not applicable.

Conflict of interest

The author(s) declare(s) that there is no competing interest.

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