Resource Recovery from Waste - Investigating the Use of Digestate as an Organic Fertiliser for Nutrient Poor Soils

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Declaration

This thesis has not been submitted in support of an application for another degree at this or any other university. It is the result of my own work and includes nothing that is the outcome of work done in collaboration except where specifically indicated. Many of the ideas in this thesis were the product of discussion with my supervisors: Prof. Kirk Semple (Lancaster Environment Centre) and Prof Ian Dodd (Lancaster Environment Centre); and Prof. Emeritus Alastair Martin (Engineering).
This thesis word length is 58920 (including table legends, figure captions, and reference lists) and therefore does not exceed the permitted maximum.

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"If I have seen further than others, it is by standing upon the shoulders of giants". ***Isaac Newton***

Abstract

This thesis investigates the use of digestate, a by-product of anaerobic digestion, as a sustainable organic fertiliser in nutrient-poor soils, particularly in sub-Saharan Africa (SSA). Digestate has been researched for its nutrient content, notably its richness in nitrogen, which can replace or complement mineral fertilisers. Although digestate's effectiveness has been studied globally, limited research has been conducted in SSA. Through desk research and laboratory experiments, this thesis aimed to: (i) review the organic resources and impacts of digestate, (ii) characterise digestate and evaluate its use for the early growth of micro -Tom tomatoes in a laboratory greenhouse, (iii) test the impact of digestate on soils, and (iv) assess the effect of irrigation and different digestate application rates on plant productivity and yield of micro-Tom tomatoes. Key findings reveal that plants treated with digestate exhibit higher above-ground biomass than those in unamended soil, demonstrating improved nutrient uptake. Increased application rates of digestate also correlated with higher retention of available nitrogen in the soil. However, no significant differences were observed in microbial biomass, soil pH, electrical conductivity, or between various water application rates and digestate application strategies. Further detailed results from three experimental scenarios illustrate varying effectiveness. In the first scenario, digestate increased crop yields by 55-65% compared to unamended soil, though it was less effective than urea fertiliser. The second scenario showed that both digestate and nitrogen-phosphorus fertilisation raised nutrient levels, albeit without significant differences between application rates. The third scenario confirmed no significant impact of fertiliser type or water regime on yield outcomes. This study concludes that while digestate can enhance soil fertility and

crop yields, its performance does not consistently surpass that of traditional mineral fertilisers.

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List of Abbreviations and Acronyms

%	Percentage
±	plus or minus
°C	degree Celsius (unit of temperature)
µg	Micrograms
Vs	Versus
Y	Year (s)
C	Carbon
CH_4	Methane
$CHCl_3$	Chloroform
CHN	Carbon Hydron Nitrogen
CE	Circular Economy
Et al	And Others
Ecowas	Economic Community of West Africa States
EC	Electrical Conductivity
G	Gram
GHG	Green House gases
Ha	Hectare
H	Hour(s)
H^+	Hydrogen Ion
K_2SO_4	Potassium Per sulphate
Kg	Kilogram
KCl	Potassium Chloride
M	Molar Mass
OM	organic matter

Ppm	part(s) per million
$PO_4{}^{3-}$	Orthophosphate
P	Level of significance
TN	Total Nitrogen
TP	Total Phosphorus
TK	Total Potassium
LE	Linear Economy
RE	Renewable Energy
SSA	Sub-Saharan Africa
SDG	Sustainable Development Goals
AD	Anaerobic digestion
N	Nitrogen
P	Phosphorus
MBN	Microbial Biomass Nitrogen
MBC	Microbial Biomass Carbon
MBP	Microbial Biomass Phosphorus
$NO_3{}^{-}$	Nitrate
$NO_2{}^{-}$	Nitrite
$NH_4{}^{+}$-N	Ammonium Nitrogen
$NO_3{}^{-}$- N	Nitrate – Nitrogen
ISR	Inoculum to Substrate Ration
VOC	Volatile Organic compounds

1 Introduction

1.1 The Linear Economy (LE) of Africa

The Linear Economy (LE) model, traditionally characterised as 'take, make, and throw away,' has dominated for centuries but is increasingly criticised for its unsustainability. This model, which relies on a one-way flow of materials and energy, starkly contrasts with sustainable practices designed to minimise waste and promote the reuse and recycling of resources (Adam et MacArthur, 2013; Lieder & Rashid, 2016; Sondh et al., 2024). Particularly in Africa, the LE model fuels a continuous extraction of natural resources such as minerals, oil, and gas and deeply extends into in the agricultural sector, which is vital to many African economies. This leads to a rapid depletion of finite resources and results in long-term scarcity (UNEP, 2019). Moreover, the use and eventual disposal of products derived from these resources contribute to growing landfill sites and increased environmental pollution (Jarvie, 2024).

Additionally, the manufacturing and disposal processes inherent in the LE model often result in air and water pollution, habitat destruction, biodiversity loss, and public health issues across Africa (Sampath, 2014). While seemingly efficient from a production perspective, the LE model is economically inefficient due to its failure to maximise resource value by neglecting reuse, repair, and recycling practices (Signe, 2019). This approach not only perpetuates a culture of consumption and disposability but also intensifies social inequalities. Often, less developed regions disproportionately suffer the consequences of resource extraction and waste disposal without seeing equivalent economic benefits (Martin et al., 2020). Furthermore, the LE's reliance on a steady supply of raw materials significantly compromises its resilience, making it especially vulnerable to disruptions, such as resource shortages or global supply chain issues. These vulnerabilities are particularly pronounced in Africa's energy sector, which also struggles with food production, waste management inefficiencies and environmental degradation (Tan et al., 2022). Such challenges highlight the urgent need for more sustainable and adaptable economic systems in Africa. Therefore, more sustainable economic systems can provide food, energy for Africa whiles ensuring the limited pollution and promoting healthy people.

This thesis aims to explore alternative practices to the LE model, focusing on the utilisation of digestate from anaerobic digestion as a sustainable agricultural input in Sub-Saharan Africa (SSA).

1.1.1 Energy Generation Challenges in West Africa Under the LE Model

The global call for more sustainable energy technologies is becoming increasingly critical, especially in Africa, where conventional electricity generation from fossil fuels significantly contributes to environmental degradation (IEA, 2022). This reliance on fossil fuels not only intensifies global warming and climate change but also affects local ecosystems and public health (Ang et al., 2022). In West Africa, the energy sector (Table 1.1), framed within the LE model, faces substantial challenges that impact both the environment and the socio-economic framework of the region.

This prevailing LE model, characterised by a "take-make-dispose" approach, leads to systemic, infrastructural, and economic inefficiencies within the energy sector. These inefficiencies not only compromise the sustainability of energy production but also hinder economic development and deteriorate the overall quality of life in the region (Kennedy-Darling et al., 2008; Berahab, 2022). The environmental impact of these unsustainable practices is profound, leading to several problems that extend from ecological damage to a direct impact on the livelihoods and health of the local populations.

Table 1.1 Summary of the status of ECOWAS electricity sectors (Bissiri, et al., 2020) (Note: - means Data not applicable; 0 means data not available)

Country in West Africa	National electrification rate	Electricity consumption (GWh)	Net imports (GWh)	Share of electricity production by fuel - Thermal	Hydro	Renewable Energy
Benin	32%	1149	1088	Diesel, gas: 98.2%	0%	1.8%
Burkina Faso	20%	1168	423	Diesel: 94.6%	5.4%	0%
Côte d'Ivoire	62%	5800	-1858	Gas: 82.5%	14.6%	2.9%
The Gambia	48%	149	0	Diesel: 98.1%	0%	1.9%
Ghana	84%	8416	-324	Gas: 57%	42.8%	0.2%
Guinea	20%	257	0	Diesel: 44.7%	55.7%	0.6%
Guinea-Bissau	13%	75	0	Diesel: 98.1%	0%	1.9%
Liberia	12%	73	0	Diesel: 100%	0%	0%
Mali	41%	3059	663	Diesel, gas: 64.4%	32.9%	2.7%
Niger	11%	975	779	Diesel, steam coal, gas: 99%	0%	1%
Nigeria	61%	25308	0	Gas, steam gas: 81.7%	18%	0.3%
Senegal	64%	3734	297	Diesel, steam heavy	7.9%	1.6%

				fuel oil, gas: 90.5%		
Sierra Leone	9%	133	0	Diesel: 43.4%	53.7%	2.9%
Togo	35%	1248	1140	Diesel, gas: 8.2%	83.2%	8.6%

A critical issue in these challenges is West Africa's heavy reliance on non-renewable energy sources (Table 1.1 Summary of the status of ECOWAS electricity sectors (Bissiri, et al., 2020) (Note: - means Data not applicable; 0 means data not available)) notably oil and gas. For example, Nigeria, the continent's top oil producer, relies heavily on these resources for its energy, linking the region's economic and energy sectors to the fluctuations of global oil markets (Awodumi and Adewuyi, 2020; Graham and Ovadia, 2019). This dependency exposes the region to global market volatilities and causes severe environmental harm through oil spills, gas flaring, and other damaging practices (Emoyan, 2008).

Furthermore, West Africa struggles with outdated and insufficient energy infrastructure, such as aging power plants and inadequate transmission and distribution networks, which are often poorly maintained (NRC, 2012). These infrastructural shortcomings result in frequent power outages and an unreliable electricity supply, severely hindering industrial development and improving living standards. The lack of modern and efficient infrastructure investment can be attributed to financial constraints and governance issues, including corruption and mismanagement (Batinge et al., 2019, World Bank 2023; Adedeji, 2016). The combined effect of these infrastructural and accessibility issues highlights the urgent need for comprehensive reforms and investment in the energy sector to foster sustainable development in West Africa.

Despite these considerable challenges linked to the LE paradigm, the situation also presents opportunities for a transformative shift toward renewable energy (RE) sources. Such a shift could mitigate some of the inherent problems of the linear model by promoting sustainable and RE practices that enhance both economic and environmental resilience (Fiksel, 2006) in West Africa.

1.2 Renewable Energy (RE) Potential and Challenges

The potential for RE in west Africa is significant and varied, reflecting the broader potential of many regions in SSA. West Africa's current energy infrastructure (Table 1.1) heavily depends on fossil fuels and natural gas (Bissiri et al., 2020). Others include hydroelectric power, which, while renewable, has faced challenges due to an insufficient supply to meet the increasing demand. This energy deficit is worsened by regular power blackouts, gas shortages, decreased oil production, and rising fuel costs (Cherp et al., 2012).

As of late 2023, approximately 745 million people globally lack access to electricity, with SSA accounting for about 600 million of this number, representing a significant 80% of the global population without access to this essential service (IEA, 2023). This statistic highlights the acute need for energy solutions in SSA.

West Africa has potential in renewable resources, including biomass, solar, wind, and potentially geothermal energy. These resources present a crucial opportunity to diversify the region’s energy mix, reduce dependence on imported fossil fuels, and foster a more stable and sustainable energy supply, supporting economic growth and poverty alleviation (Aliyu et al., 2023).

The current linear economic model underutilises organic waste, which could be converted into biogas - an RE source. Instead, organic materials accumulate in landfills, missing the opportunity for energy recovery and exacerbating greenhouse gas emissions (Ayeleru et al., 2018; Jarvie, 2024). Transitioning to a RE framework through the circular economy (CE) model could revolutionise energy generation and create a more sustainable economy in West Africa.

However, despite promising RE prospects, West Africa faces considerable challenges, including the high costs of renewable infrastructure, lack of technological expertise, and policy gaps that do not sufficiently encourage renewable investments. Integrating RE sources into the existing grid also introduces complexities due to the intermittent nature of sources like solar and wind (Mutezo and Mulopo, 2021).

Effective energy policies and modern regulatory frameworks are essential to promote a conducive environment for the advancement of RE (Nyarko et al., 2023). Many current policies in West African countries are either outdated or poorly implemented (Nabyonga-Orem et al., 2021). A robust policy framework should facilitate investments, emphasise sustainability, and promote environmental stewardship Furthermore, regional collaboration is crucial to overcome transnational energy trade challenges, optimise resource allocation, and standardise regulatory measures to enhance energy security (Rudd, 2004).

Addressing the energy generation issues in West Africa requires joint efforts from local governments, the private sector, and international stakeholders. Investments in upgrading energy infrastructure, expanding electricity access, adopting RE, and strengthening regulatory systems are vital for establishing a sustainable and reliable energy setup. Such a comprehensive approach not only promises to elevate economic prospects but also improve the living conditions of the populace. While pursuing the outlined strategy, leveraging waste resources to generate energy could serve as a pivotal initial step towards embracing RE solutions.

1.3 The Need for Resource Recovery and Waste Valorisation in Africa

1.3.1 Growing Waste Challenges

Africa is grappling with escalating waste production due to rapid urbanisation, significant population growth, and economic advancement, occurring alongside deficient waste management infrastructures (Maalouf and Agamuthu, 2023; Turok, & McGranahan, 2013).). As the continent develops, the volume of waste generated is projected to rise dramatically, from 174 million tonnes in 2016 to an estimated 244 million tonnes by 2025 (UNEP, 2024). This increase poses severe challenges for environmental and public health, as well as economic stability, particularly as a substantial portion of waste, especially in rural and underserved urban areas, remains uncollected. Typically, municipal solid waste (MSW) in Africa comprises 57% organic matter and 13% plastics, with the remainder consisting of metals, glass, and an increasing quantity of electronic waste (Godfrey et al., 2019). Currently, only about 4%

of waste is recycled, leading to over 90% of the continent's waste ending up in open dumps or poorly managed landfills, which create significant environmental hazards from leachate and methane emissions (Gebremedhin et al., 2018).

1.3.1.1 Waste Management Deficiencies in West Africa

West Africa is experiencing its own waste management crisis, exacerbated by the expanding urban centres like Lagos, Accra, and Abidjan, which contribute significantly to the region’s waste challenges (UNEP, 2018). Lagos alone produces over 10,000 metric tons of waste daily, often mishandled due to subpar management practices (Agunbiade, 2014). The economic activities in West Africa produce a diverse mix of waste, including substantial amounts of organic matter and electronics. Furthermore, plastic pollution poses a particular concern, leading to blocked waterways, flooding, and significant environmental pollution (UNEP, 2018). The handling of hazardous wastes, such as medical and industrial refuse, is increasingly problematic, with improper disposal methods resulting in environmental contamination and public health hazards (Ayeleru et al., 2020). Notably, rural areas often lack any waste management infrastructure, leading to common practices of waste burning or disposal in local water bodies, which worsen environmental and public health challenges (Viljoen et al., 2021).

1.3.2 Strategic Responses and the Shift to Circular Economy (CE)

The multifaceted waste production dilemma in West Africa, reflective of broader continental challenges, encompasses social, economic, and environmental dimensions

(Ayeleru et al., 2020). A comprehensive response is imperative, demanding enhanced infrastructure, robust waste management systems, efficient collection, recycling capabilities, and sanitary landfills (OECD, 2018). Additionally, promoting waste reduction, reuse, and recycling through public education campaigns and incentives, and formalising the informal sector by integrating waste collectors into the formal economy with the necessary tools, training, and recognition, can significantly improve operational efficiency and working conditions (Ayeleru et al., 2020). This collaborative approach is vital to develop sustainable and integrated waste management solutions tailored to the specific needs and contexts of West African countries.

Moreover, the pressures of volatile commodity prices and resource scarcity exacerbate these challenges, squeezing farmers' already narrow profit margins and highlighting the need for a shift from the linear 'take-make-dispose' model to a more sustainable circular economy that enhances waste valorisation and promotes sustainable agricultural practices (Kliesen, 2021).

1.3.3 The Urgent Need for a Transition to a Circular Economy (CE)

Transitioning to a CE represents a fundamental shift towards sustainability, particularly pertinent to agriculture (Abbasi et al., 2024). This economic system, aimed at eliminating waste and continually using resources, follows a 'reduce, reuse, recycle' principle, contrasting sharply with the linear model (Lazarevic, & Brandão, 2020). By redesigning resource life cycles so that all products are reused, and nothing is wasted, the CE keeps resources in use for as long as possible, extracts the maximum value from them while in use, and recovers and regenerates products and materials at the end of each service life. In agriculture, adopting a circular model can dramatically alter socio-economic practices, leading to reduced reliance on synthetic inputs, enhanced soil regeneration, and the transformation of agricultural waste into valuable inputs (Boon & Anuga, 2020). This shift not only addresses the unsustainability highlighted by the linear model but also aligns with Kenneth Boulding's vision of the "spaceship economy," which emphasises Earth's finite resources and the need for a sustainable management system (Boulding, 1966). Further developed by Pearce and Turner (1990), the CE concept advocates for a "closed" system that maintains an equilibrium between resource usage and waste generation (Figure 1.1). To effectively implement this paradigm, shift in African agriculture, it is crucial to focus on resourcefulness and regeneration. This involves rethinking production, consumption, and waste management practices, and investing in innovative approaches that add value throughout the lifecycle of materials and products (Martinez-Blanco et al., 2009). Supporting the circular transition requires policies that encourage the recycling and use of recycled materials, significant investments in modern recycling facilities and RE infrastructure, and robust public awareness campaigns and educational initiatives to cultivate a sustainability-minded generation (Aithal & Aithal, 2023). Moreso, by valorising waste, that is, converting it into more useful products or resources, African nations can ensure long-term environmental resilience and economic stability, ultimately fostering a more resilient and sustainable food system (Okuthe, 2024).

1.4 Circular Economy (CE)

Figure 1.1 is an exemplary representation of the CE, which advocates for a sustainable approach to the interconnectedness of waste management, energy production, and food systems. Strategically waste to resource transformation could be an effective waste management approach which may mean that part of the organic wastes could be used for biogas production through anaerobic digestion for domestic and commercial use. Other central role of CE is discussed below in section 1.4.2 to section 1.4.3.

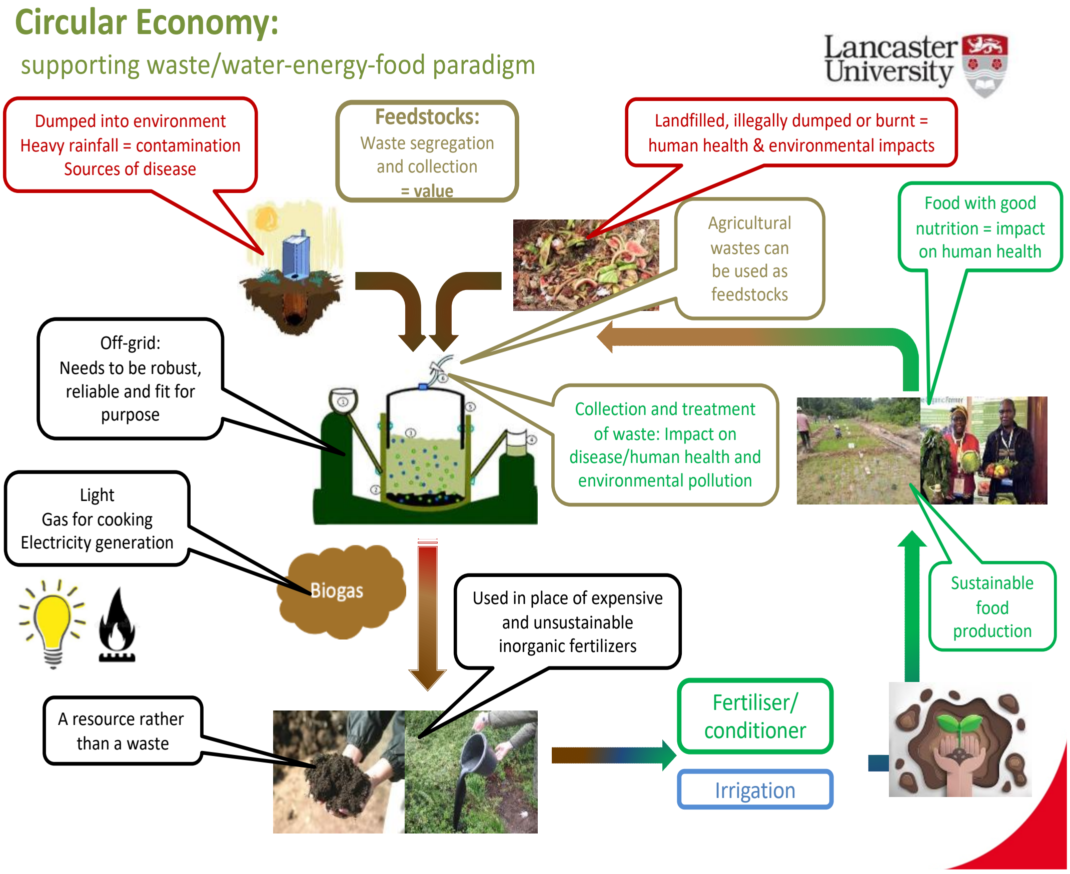

Figure 1.1: Model of Circular Economy

1.4.1 Waste to Resource Transformation

Central to the CE is the transformation of waste into resources (Kalkanis et al., 2022). In a CE, waste materials are viewed not as trash but as valuable resources that can be recycled and reused in production cycles. This approach reduces environmental impacts and promotes sustainability by transforming waste into feedstock for other processes

(Viljoen et al., 2021**)**. For example, in West Africa, common waste materials such as coconut shells, cassava peels, and palm kernel shells can serve as feedstock. Coconut shells can be converted into activated carbon, which is used in water purification and air filtration systems (Arena et al, 2016). Cassava peel, often discarded in large quantities, can be processed into animal feed, or used to produce biogas through anaerobic digestion, providing an alternative energy source (Ismail et al, 2022). Palm kernel shells are a by-product of the palm oil industry and can be used as biomass feedstock in bioenergy production to generate electricity (Okoroigwe and Saffron, 2012).

These practices contrast sharply with traditional waste disposal methods like landfilling, illegal dumping, or burning, which pose significant threats to environmental integrity and human health. By adopting a CE model, West Africa and all SSA can mitigate these risks by effectively turning typical waste streams into useful raw materials that contribute to economic and environmental sustainability (Tan et al., 2022).

1.4.2 Biogas Generation and Utilisation

A pivotal component of CE is the production of biogas from organic waste. In this closed-loop system, anaerobic digestion is employed to convert organic matter into biogas, which can subsequently be used for lighting, cooking, and electricity generation (Gandhi et al., 2022). The conversion process serves dual purposes. Firstly, provides a renewable source of energy and secondly reduces the reliance on unsustainable inorganic fertilisers using the by-product. This approach not only conserves natural resources but also mitigates the harmful environmental impacts of conventional energy sources. A practical example of this is seen in Rwanda's waste-to-energy plant in Kigali, which processes local agricultural waste into biogas, significantly reducing landfill use and providing energy to local communities (Nikuze, 2020). Other examples are present in Table 1.2 Biogas plants present in some African countries treating solid wastes (Surroop et al., 2019; Kemausuor et al., 2018). These biogas plants installed utilises waste from food, market, animal, agricultural and municipal solid wastes as feedstocks.

Table 1.2 Biogas plants present in some African countries treating solid wastes (Surroop et al., 2019; Kemausuor et al., 2018)

Area	Developer or biomass source or name of Biogas plant	Capacity (MW)	Number of solid wastes treated/accepted	Country
Ouagadougou	Fasobiogaz SARL	0.275	40 tpd of slaughterhouse and brewery wastes	Burkina Faso
Asesewa	Asesewa	0.095	n.d	Ghana
Ashalman	Ashalman	0.1	n.d	Ghana
Kwae	Kwae	0.2	n.d	Ghana
Naivasha	Gorge Farm Energy Park	2.8	50,000 tpa of agricultural wastes	Kenya
Isinya	Slaughterhouse waste	0.03	n.d	Kenya
Keekonyokie	P. J. Dave Flowers Ltd (PPP)	0.03	n.d	Kenya
Kericho	Slaughterhouse waste	0.02	n.d	Kenya
Kilifi	James Finlay Ltd	0.16	n.d	Kenya
Naivasha	Naivasha	0.15	n.d	Kenya
Sagana	Sagana	2.2	n.d	Kenya
Natasha	Natasha	0.3	n.d	Kenya
Simbi Roses	Simbi Roses	0.055	n.d	Kenya

Alice	University of Port Hare	0.2	n.d	South Africa
Athlone	Clean Energy Africa and Wastemart	4	n.d	South Africa
Bredasdorp	Ibert	0.1	n.d	South Africa
Cavalier	Ibert	0.5	n.d	South Africa
Cavalier	EnviroServ/Chloorkop LFG	0.19	n.d	South Africa
Darling Uilenkraal	Uilenkraal dairy farm	0.6	n.d	South Africa
Durban	Culnan	0.6	n.d	South Africa
Durban	Bissar road LFG	6	n.d	South Africa
Durban	Marianhill LFG	1.5	n.d	South Africa
Grabouw	Elgin Fruit and Juices	0.5	n.d	South Africa
Jan Kempdorp	Ibert	0.135	n.d	South Africa
Jan Kempdorp	Jacobstal	0.15	n.d	South Africa
Johannesburg	WEC Projects/Northern Wastewater Treatment Works	0.12	n.d	South Africa
Johannesburg	Robinson Deep	19.9	n.d	South Africa
Klipheuwel	Farmsecure	0.60-0.70	n.d	South Africa
Mossel Bay	Biothern Energy	4.2	n.d	South Africa

Paarl	Drakenstein municipality	14	n.d	South Africa
Pretoria	Pretoria	4.6	n.d	South Africa
Riverdale	Riverdale	0.1	n.d	South Africa
Riversdale	Riversdale	0.15	n.d	South Africa
Springs	Selectra	0.5	n.d	South Africa
Springs	Selectra	1	n.d	South Africa
Springs	Selectra	1	n.d	South Africa
Chaka Dagoretti	Afrisol	0.06	n.d	South Africa
Bronkhorstspruit	Bio2Watt's biogas plant	4.6	120,000 tpa of agricultural wastes	South Africa
Athlone (Cape Town)	New Horizons waste-to-energy plant	nd	560 tpd of household, municipal and industrial solid wastes	South Africa
Springs	Morgan Abattoir biogas plant	0.4	Slaughterhouse wastes (Amount not available)	South Africa
Grabouw	Elgin Fruit Juices biogas facility	0.5	>5 tpd of waste fruit	South Africa
Bir El Kassaa	SOTUMAG biogas plant	0.13	25 tpd of market wastes	Tunisia

Note: tpd (tons per day); nd (no data captured)

1.4.3 Enhancing Agricultural Practices

In a CE, agricultural waste acquires a new lease on life as feedstock, leading to sustainable food production practices (Kalkanis et al., 2022). The use of anaerobic digestion by-products as fertilisers or soil conditioners enriches the soil, reduces the dependency on harmful chemical fertilisers, and promotes sustainable agricultural practices. The interlinkage of waste management and food quality highlights the circular economy's potential to enhance nutritional outcomes, thus having a direct positive impact on human health (Kalkanis et al., 2022).

1.5 Benefits of Waste Valorisation under CE

1.5.1 Environmental Benefits

Implementing a CE offers significant environmental and public health benefits (Tan et al., 2022). CE systems are designed to promote the reuse, recycling, and recovery of materials in production processes and reduce waste. CE systems aim to keep resources in use for as long as possible, extract the maximum value from them while in use, and then recover and regenerate products and materials at the end of each service life. Most of the time CE systems are designed to be off-grid and robust, enhancing disease control and reducing environmental pollution. For instance, these systems mitigate issues such as contamination spread by heavy rainfall, thus safeguarding community health and well-being (Wang, et al., 2022; Al-Wabel et al., 2022).

CE practices include waste valorisation, which significantly decreases the volume of waste directed to landfills, reducing land pollution and the associated long-term environmental problems, such as soil and water contamination from leachate. By diverting waste from incinerators and dumps, waste valorisation also minimises air, water, and soil pollution (Chojnacka et al., 2021). Recycling efforts, such as in plastics, reduce toxic emissions from burning, while the use of organic waste in biogas production decreases methane emissions from landfills and contributes to sustainable energy generation (Table 1.2).

Additionally, valorisation supports material reuse, which curtails the demand for new resource extraction, thereby conserving natural habitats and biodiversity (Arena et al., 2016). A notable example is Sanergy in Nairobi, Kenya, which has developed a sustainable model to collect and process waste from informal settlements into organic fertiliser, enhancing sanitation and providing local farmers with an efficient soil amendment (Peletz et al., 2020).

1.5.2 Economic Benefits

The economic benefits of waste valorisation are both direct and far-reaching, catalysing the creation of new sectors within the CE and leading to robust economic development and sustainability (Ramakrishna, 2022). Renewable energy from CE systems has the potential to fulfil a substantial portion of Africa's energy demands, offering numerous advantages for the region such as environmental enhancement, greater diversity of fuel sources, and improved energy security (Abeeku et al., 2008). This sufficient energy transformation can birth new industries across a range of economic activities including collection, sorting, processing, and manufacturing, which not only add economic value but also create diverse job opportunities (Lieder & Rashid, 2016). For instance, the bioenergy production industry needs skilled operators for management, engineers for system upkeep, and workers for material sorting and processing (Okoroigwe and Saffron et al., 2012). Similarly, composting and recycling operations require employees proficient in waste management and logistics, offering job opportunities for people with various skill sets and bolstering economic development in areas suffering from high unemployment. Particularly in rural areas, the output of waste valorisation processes, such as compost and biochar, serves as a critical agricultural enhancement, improving soil fertility and water retention, boosting crop yields, and enhancing the economic well-being of farming communities (Viljoen et al. 2021). Moreover, the need to manage waste more effectively drives innovation in waste processing technologies, developing new methods that stimulate technological advancements and position regions as leaders in green technologies, thus attracting further investment from both domestic and international sources interested in capitalising on innovative and sustainable business ventures (NPC, 2019). As global awareness of environmental sustainability increases, waste valorisation projects present attractive investment opportunities that not only fund the development of new technologies and facilities but also bring additional economic benefits to local communities, such as improved infrastructure and increased local spending, making waste valorisation a significant economic driver that contributes to a more sustainable and prosperous economic future (Ramakrishna, 2022).

1.5.3 Social Benefits

Proper waste management reduces the prevalence of diseases related to waste, such as respiratory infections from polluted air and waterborne illnesses from contaminated water supplies (Chojnacka et al., 2021). Engaging communities in recycling programs can foster a sense of responsibility and pride, leading to overall social development (Hopper & Nielsen, 1991). Waste valorisation efforts can be accompanied by educational programs that raise awareness about environmental issues, promoting sustainable practices. By providing jobs and economic opportunities, waste valorisation can play a role in reducing poverty and increasing social inclusion, particularly for the marginalised sectors of society (Viljoen et al., 2021).

1.5.4 Policy and Infrastructure Development

Waste valorisation under the CE framework necessitates robust governmental and institutional support to realise its full potential, particularly in the promotion of commercial biogas projects in Africa. Adopting CE will ensure effective policies and frameworks essential to address the barriers hindering the adoption of these projects across the continent will be curtailed. Instruments such as Feed-in Tariffs, quota obligations, and competitive bidding programs crucial, yet facing implementation challenges will be handled effectively (Kemausour et al., 2018). In a report by GIZ, (2018), South Africa has the high costs associated with bidding processes for biogas to grid which can deter investors. This indicates the need for policy refinement to make grid access more accessible and equitable, similar to models in Ghana and Nigeria where approved biogas plants have guaranteed grid access (Kemausour et al., 2018). Adopting a CE framework will help cut down costs and or processes needed for the adoption of sustainable energy policies.

Moreover, the enforcement of environmental laws which often poses significant challenges, as seen in East African countries such as Tanzania, Malawi, Uganda and Ethiopia where wastes are commonly disposed of indiscriminately (Kemausour et al., 2018). To address this integrating commercial biogas systems into national waste management frameworks will not only offer sanitation and energy benefits but also aligns with environmental policies that mandate the proper management of bio-waste. This compliance stimulates the construction of biogas plants, particularly in regions with strict waste management regulations (Bharat et al, 2020).

Globally, the experiences of countries like China and Germany illustrate the efficacy of targeted environmental regulations in promoting the growth of biogas facilities (Chen et al., 2017; Daniel-Gromke, 2018). China demonstrates the impact of targeted environmental regulations on the proliferation of biogas facilities. Chinese policies specific to pollution control in livestock and poultry production have encouraged the adoption of biogas technology, which facilitates efficient recycling of manure and contributes to energy production (Chen et al., 2017). Similarly, regulations in Germany restricts the disposal of municipal solid waste (MSW) to landfills. This move has bolstered the demand for biogas plants, showcasing a proactive approach to waste management and methane emission reduction (Kemausour et al., 2019; IRENA, 2018; Daniel-Gromke, 2018).

In the same sense, African countries could benefit from emulating such regulatory frameworks to bolster their biogas sector, with an emphasis on AD technologies that can efficiently convert waste into energy (Abeeku et al., 2008). By establishing stricter regulations and promoting waste segregation, especially in urban areas, governments can foster a conducive environment for biogas technology, linking it not only to direct economic benefits but also to broader environmental improvements (Kemausour et al., 2018).

To capitalise on these advantages, it is critical for African nations to enforce existing policies rigorously and consider adopting new ones that are responsive to both local and global renewable energy trends. This commitment should be mirrored in regional efforts, such as those by the Economic Community of West African States (ECOWAS) and the East African Community (EAC), which have set ambitious renewable energy targets. Ensuring these targets are not merely aspirational but actively pursued and enforced will be essential for the continent's progress in renewable energy integration and sustainable waste management (Kemausour et al., 2018).

1.6 Valorisation of waste via Anaerobic Digestion Principles and Applications

1.6.1 Principles of Anaerobic Digestion (AD)

Anaerobic digestion (AD) is a biological process that decomposes organic materials in the absence of oxygen, transforming waste into valuable by-products like biogas and digestate (Gandhi et al., 2022). Biogas is primarily composed of methane (CH_4) (40 – 75%) and carbon dioxide (CO_2) also forming a significant part (15 – 60%) and minor amounts of other gases including hydrogen sulphide (H_2S) (0.005 – 2%), nitrogen (0 –

2%), oxygen (0–1%), ammonia (<1%), carbon monoxide (<0.6%), siloxanes (0 – 0.2%), and halogenated hydrocarbons (VOC, <0.6%) (Atelge et al., 2020).

The AD process is increasingly recognised for its potential to contribute to sustainable waste management and energy production. The AD process (Figure 1.2) occurs in four primary stages hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Jarvie, 2023). During the hydrolysis stage, large organic polymers in the waste, such as carbohydrates, proteins, and fats, are broken down into smaller molecules like sugars, amino acids, and fatty acids. In the acidogenesis, the products of hydrolysis are further converted into volatile fatty acids, alcohols, hydrogen, and CO_2 by acidogenic bacteria.

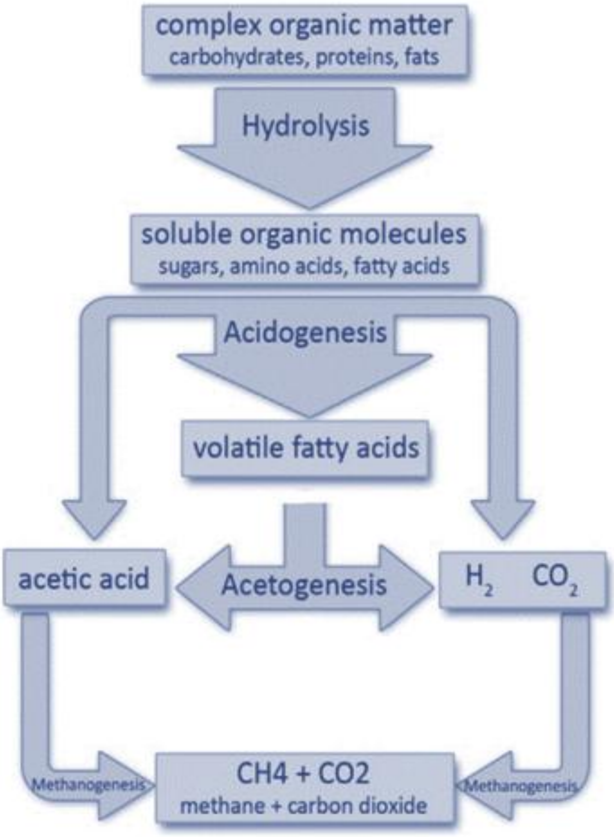

Figure 1.2 The Anaerobic Digestion Process (Fagbohungbe et al., 2017)

In acetogenesis stage the acidogenic products are transformed into acetic acid, H_2, and CO_2, which are direct precursors for the final stage of methanogenesis. During the final stage, which is the methanogenesis stage, methanogenic archaea convert intermediates such as acetic acid, H_2, and CO_2 into CH_4 and water. Methane (CH_4), a primary component of biogas, can be used as a fuel. These stages collectively convert organic waste into methane-rich biogas and nutrient-rich digestate, each offering significant environmental and economic benefits (Gandhi et al., 2022; Jarvie, 2023; Atelge et al., 2020)

1.6.2 Challenges and Future Prospects

The challenges in the anaerobic digestion (AD) process include feedstock variability, low process efficiency, and lower quality by-products (Uddin & Wright, 2023). Variability in the physical and chemical properties of feedstocks complicates technology selection and optimal process conditions. Efficiency issues stem from complex interactions among bacteria and the buildup of inhibitory substances like ammonia and fatty acids, which can disrupt methane production. The main product, biogas, has a lower energy content than natural gas due to its high CO_2 content, and managing the high volume and moisture content of digestate can presents logistical and economic challenges. In addition to these hurdles, AD has high initial setup and operational costs, and it requires a consistent feedstock supply and technical optimisations (Uddin & Wright, 2023).

Despite of the above challenges mentioned above innovative technological solutions are being developed to overcome the inherent challenges of anaerobic digestion, focusing on enhancing process control and stability to ensure higher output and better-quality biogas (Ghandhi et al., 2022).

1.6.3 Enhancing Agriculture with Digestate in SSA

1.6.3.1 Utilisation of Digestate as a Sustainable Fertiliser

Anaerobic digestion, particularly the use of digestate in agriculture, marks a significant step towards sustainable farming practices and is considered suitable for environmental improvement (Ndambi et al., 2019). The AD process breaks down organic matter in the absence of oxygen, producing not only biogas but also generating digestate, a nutrient-rich organic fertiliser utilising digestate (Figure 1.3) from the AD process as a soil fertiliser enhances the value of this process (Singh et al., 2022). Intensive agriculture has led to soil degradation and loss of soil organic matter and fertility, hence efforts to maintain productivity have resulted in increased production costs and contributed to GHG emissions from the use of mineral fertilisers (Wood & Cowie, 2004). The use of digestate as a soil amendment can reduce the reliance on and overuse of mineral fertilisers while replacing organic and mineral matter (Mehta et al., 2022). As the SSA population grows, the demand for sustainable agricultural methods has become more pressing (Li et al., 2023). Digestate is a critical component for achieving sustainable agriculture in SSA, due to the numerous benefits it offers (Ndambi et al., 2019). High in nutrient content, digestate contains nitrogen, phosphorus, and potassium from the original feedstocks, enriches soil, and improves agricultural productivity (Lamolinara et al., 2022). The use of AD digestate as fertilisers reduces energy consumption and carbon emissions associated with mineral fertiliser production, thereby reducing reliance on fossil fuels and mitigating CH_4 emissions from organic waste (Chojnacka and Moustakas, 2024).

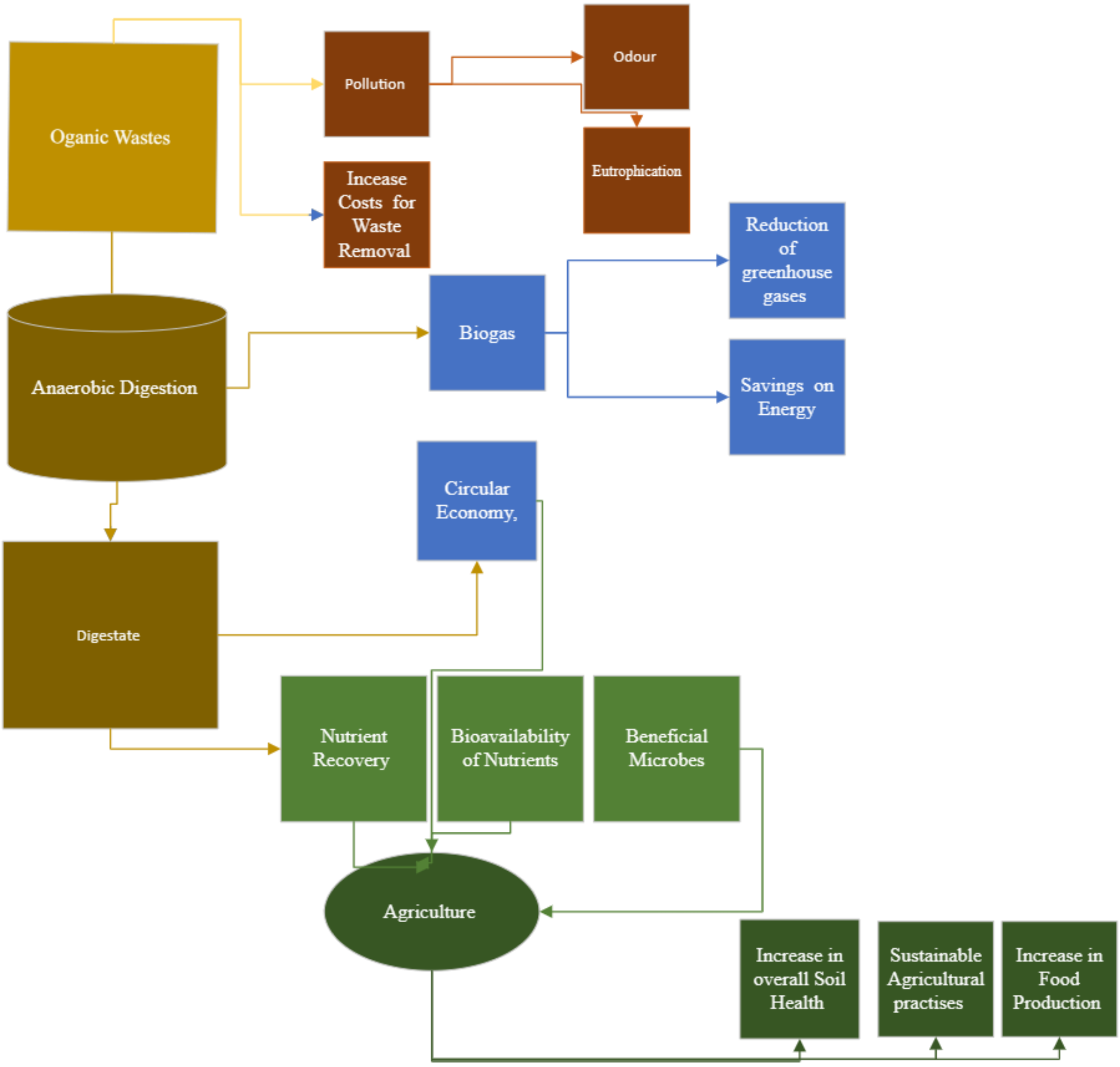

Figure 1.3 Organic Waste Resource recovery through Anaerobic Digestion

As a soil amendment, digestate offers readily available nutrients, has a broad nutrient base, and can improve soil health (Alburquerque et al., 2012). It provides a range of nutrients and organic matter, enhancing soil fertility, structure, and organic content. Utilising digestate in agriculture is a crucial step towards a sustainable future in SSA.

1.6.3.2 Agricultural Practices and Land Use in SSA

Sub-Saharan Africa (SSA) is a vast region characterised by diverse agro-ecological zones, leading to varied agricultural practices and land use patterns (World Bank, 2023). These patterns emerge from a complex interplay of socio-economic, cultural, and environmental factors. Land use in SSA includes a range of systems such as shifting cultivation (Gilruth et al., 1995; Zhang et al., 2001), pastoralism (FAO, 2018), permanent crop farming (Heidenreich et al., 2022), agroforestry (Muthuri et al., 2023), and urban agriculture (Davies et al., 2021). Shifting cultivation, which often employs slash-and-burn techniques, can lead to soil fertility depletion. Pastoralism, prevalent in arid and semi-arid regions, sometimes results in overgrazing and loss of land cover (Gonzalez and Ghermandi, 2021). In contrast, areas with favourable soil fertility and rainfall support permanent crop farming, focusing on staples like maize, millet, and cassava, as well as cash crops such as coffee, cocoa, and tea (Heidenreich et al., 2022). Agroforestry, integrating crops, trees, and livestock, alongside urban agriculture, is gaining traction in cities. Despite this diversity, fertiliser application in SSA remains minimal (Sheahan and Barrett, 2017), with a preference for organic over synthetic fertilisers due to high costs and limited access. SSA has historically reported the world's lowest fertiliser application rates. However, there have been efforts to increase the use of fertilisers alongside improved farming practices (Sheahan and Barrett, 2017).

1.6.3.3 Soil Interactions with Digestate

The use of digestate, a by-product of anaerobic digestion, is transforming sustainable agriculture practices by enriching soil health and promoting eco-friendly farming (Slepetiene et al., 2023). The rich nutrient content and organic matter of digestate make it an essential soil amendment, providing a balanced supply of nitrogen (N), phosphorus (P), potassium (K), and essential micronutrients to plants (Tiong et al. 2024). This contrasts with some synthetic fertilisers because nutrients in digestate are more bioavailable, ensuring efficient uptake and healthier crop growth with increased yields (Gurmessa et al., 2023). Additionally, previous studies showed that digestate can improve soil structure, water retention, and microbial activity which are vital for plant health and soil resilience (Nkoa, 2014; Abubaker et al., 2013). Again, the slow nutrient release from digestate (Zhang et al., 2020) can minimise environmental runoff, further positioning it as a sustainable alternative to chemical fertilisers and supporting the CE by recycling organic waste (Zhang et al., 2020). While digestate offers numerous benefits, its application must be managed carefully, considering factors such as timing, rate, and method to maximise its advantages and avoid potential issues like nutrient leaching or phytotoxicity (Wang & Li, 2019).

1.7 Problem Statement and Justification

In 2006, the Abuja declaration brought together states of the African Union to collectively recommend an increase in fertiliser nitrogen (N) use from 8 kg ha^{-1} to 50 kg ha^{-1} by 2015 to help enable SSA to achieve food sufficiency and eradicate poverty while improving the soil fertility (Ladha et al., 2020). Recent studies shows that the recommended rate of fertiliser application has not been met (Sheahan and Barrett, 2017; Sommer et al., 2013; TMP, 2013). Most of the smallholder farmers in SSA still apply less than 50 kg N/ha per year due to reduced financial capability and inadequate infrastructure to access the inputs (Sheahan and Barrett, 2017; Ladha et al., 2020). The leading consequence of this is that SSA may not achieve the sufficiency of food production it hopes to attain. Incorporating digestate as a fertiliser in SSA can significantly improve agricultural practices, considering its suitability for different soil types found across the region. Digestate, rich in nutrients, can restore soils depleted by excessive land use and enhance soil fertility in areas practicing permanent crop farming (Badagliacca et al., 2020). Digestate use in arid and semi-arid regions can improve soil water retention (Chojnacka and Moustakas, 2024), crucial for pastoralism and crop cultivation in these areas. Furthermore, the organic nature of digestate aligns with the existing preference for organic fertilisers in SSA (Schader et al., 2021; Smith et al., 2014). Incorporating digestate can provide a sustainable and locally available fertiliser for agroforestry and urban agriculture (Smith et al., 2014). The product can increase productivity of both crops and trees (Chojnacka and Moustakas, 2024) while maintaining soil health countering land degradation. Therefore, promoting the use of digestate as a fertiliser in SSA aligns with sustainable agricultural practices (Li et al., 2023) which is in line with the sustainable development goals (SDG 7, 13) and improves soil health across various farming systems whiles addressing key challenges (SDG 2 and 13) in the region (Rubagumya, 2023).

1.8 Digestate as Fertilisers for Early Growth of Tomatoes

Tomatoes, an ingredient in many staple dishes and sauces in SSA, thrive in nutrient-rich soil, especially during their early growth stages (FAO, 2023; Bindra, 2023). Traditionally, mineral fertilisers have been the primary nutrient source for most farmers (Bindra, 2023). However, the increasing focus on sustainable agriculture has brought attention to alternatives like digestate. Unlike conventional fertilisers, digestate offers a rich blend of essential nutrients, including nitrogen (N), phosphorus (P), potassium (K), and various micronutrients, in forms readily accessible to plants (Zhang et al., 2020; Slepetiene et al., 2020; Fagbehunbe et al., 2017). This makes digestate a sustainable and directly beneficial choice for the early growth stages of tomato plants, providing a targeted nutrient supply that meets their specific developmental needs. For instance, Cristina et al. (2020) observed significant increases in tomato biomass and height, up to 37.5% and sixfold respectively, when digestate derived from sewage sludge was applied at a rate of 170 kg N/ha, without any phytotoxic effects. This study, along with others, suggests that digestate can enrich soil with both macro- and micro-nutrients, thereby enhancing plant nutrient uptake and organic matter content.

However, research also reveals variability in the effectiveness of digestate-based fertilisation. Dahunsi & Ogunrinola (2018) reported improved morphological traits and soil microorganisms in tomatoes with higher applications of biofertilisers, although the exact rate of application was not specified. Conversely, Mupambwa et al. (2019) found that hydroponic tomato cultivation with cow-based digestate yielded lower compared to chemical fertilisation, suggesting that not all types of digestate may be suitable as nutrient media. Asp and Bergstrand's study (2024) further emphasised this variability, noting that while digestate fertilisation contributed to biomass production, it did not match the output achieved with mineral fertilisers. Specifically, treatments with digestate resulted in only 62% and 47% of the total biomass and a similar reduction in yield of harvestable fruits compared to the mineral-fertiliser reference.

Tomato plants require nitrogen (N) of 150 to 200 kg/ha, phosphorus (P) 30 to 80 kg/ha, and potassium (K) 150 to 200 kg/ha (Tavallali et al., 2018). During the initial growth phase, tomatoes require a balanced nutrient supply for healthy development (Ahmed et al., 2023). The high nitrogen content of digestate products is particularly beneficial for early leaf development, while phosphorus supports strong root growth, and potassium aids in fruit development, overall plant health, and disease resistance (Das et al., 2022; Tiong et al., 2024). Using digestate as a fertiliser supports healthy plant growth and aligns with sustainable practices by reducing the need for energy-intensive synthetic fertilisers (Slepetiene, 2024), thereby cutting down carbon footprints and offering economic benefits for farmers in SSA with limited access to commercial fertilisers. However, due to the delicate nature of tomato seedlings, the digestate should be well digested and devoid of any potential phytotoxicity to avoid harm to the plants.

According to Wang et al. (2023), characteristics of digestate for land application must include high nutrient content and low levels of pathogens, maintain a neutral to slightly alkaline pH (Schilling et al., 2000), emit reduced odours (Pilgrim et al., 2010), and exhibit a consistent composition, suggesting a uniform physical and chemical makeup. Furthermore, it should generate lower greenhouse gas (GHG) emissions (Pilgrim et al., 2010) and contain significant levels of micronutrients with low levels of contaminants. The nutrients within the digestate should be readily bioavailable. Recognised forms of digestate for land application are whole, liquid, solid, processed, and dried or pelletised (Tambone et al., 2010; Haraldsen et al., 2010; Ehmann et al., 2018; Nolan et al., 2022;

Gurmessa et al., 2024; Moshkin et al., 2023). Regardless of the type used, digestate must exhibit the characteristics to ensure optimal conditions for growth.

The hypotheses tested in this research were examined through a combination of controlled laboratory experiments and modelling approaches, among other methods. They are:

1. Increased fertiliser application and crop yields - Applying more fertilisers will lead to higher crop yields in SSA compared to scenarios where no fertiliser amendments are made.
2. Long-term soil health with mineral fertilisers - The continuous use of synthetic fertilisers, without the addition of organic matter, will negatively affect long-term soil health. This will be observed through changes in soil available nitrogen (NH_4^+-N and NO_3^--N), pH, electrical conductivity, and microbial biomass, highlighting the potential disruption of soil microbial ecosystems essential for sustaining soil health over time.
3. Digestate fertilisation vs. inorganic fertilisers - Digestate fertilisation is hypothesised to enhance the physical and chemical properties of soil more effectively than synthetic fertilisers in SSA farmlands, including improvements in nutrient availability, soil structure, moisture retention, and microbial activity.
4. Achieving soil health through fertilisation - Regular and appropriate application of fertilisers (both inorganic and organic) is crucial for maintaining soil health and quality, suggesting that a balanced and informed approach to fertilisation can lead to sustainable soil management practices.

1.9 Developing A New Set of Optimal Rates for Applying Digestate; A Context for This Research Initiative

The RECIRCULATE Project, funded by the UK Research and Innovation Global Challenges Research Fund (UKRI GCRF), represents a significant interdisciplinary research initiative designed to address crucial environmental and societal challenges within African communities. By focusing on the transformative concept of the water-energy-food nexus, the project seeks to promote sustainable practices and eco-innovations through the efficient management and reuse of wastewater. This initiative stands as a foundation in advancing knowledge and developing novel methodologies that contribute significantly to improving water quality and safety, crucial for both human health and agricultural productivity.

This thesis is aligned with the initiatives undertaken within the framework of the RECIRCULATE Project. The project embodied an interdisciplinary, co-designed research endeavour aimed at devising innovative solutions to the critical issues surrounding water usage and safety. THE RECIRCULATE Project integrated various aspects of the role of water in sustaining communities, encompassing sewage disposal, energy generation, and its application in food production. Firstly, the project addresses sewage disposal by exploring innovative wastewater treatment technologies that not only clean water but also recover nutrients and energy, turning a waste disposal problem into an opportunity for resource recovery. Secondly, in terms of energy generation, the project investigates the potential of biogas production from treated wastewater and organic waste, which can provide a renewable energy source for local communities and contribute to reducing reliance on non-renewable resources. Lastly, the project examines water's role in food production by implementing and testing systems that use treated wastewater for irrigation and fertilisation in agriculture. This not only improves water efficiency and availability for crop production but also enhances soil health by reintroducing essential nutrients through organic means.

This thesis is aligned with the initiatives undertaken within the framework of the project. The project embodied an interdisciplinary, co-designed research endeavour aimed at devising innovative solutions to the critical issues surrounding water usage and safety.

Addressing these challenges necessitated a novel research methodology and the effective translation of research outcomes to cater for the needs of African communities. This research project contributed to this overarching goal by exploring and developing new strategies for sustainable water management and safety protocols.

Across partners and across disciplines, and working with business and other research users, the research co-designed research to deliver appropriate solutions for Africa, building on cutting-edge solutions to addressing the global challenges around safe and sustainable water use. This project received financial support from GCRF research fund. The RECIRCULATE Project focused on resource recovery from waste namely food, animal waste to some extent municipal waste.

This research focused on the use of the by-product from the bioenergy generation for agriculture. Different fertilising materials were also sourced and considered for the work. During the three years of the project, researchers have worked together to develop and optimise biogas production, reduction of pathogens and agriculture soil and plants application of treated AD digestate in laboratory-based greenhouse. Similar materials were used to carry out a field research work in Ghana. The digestate was applied and compared with urea fertilisers at an application rate of 22.5 to 100 kg/N/ha, common in West Africa and Ghana in particular (Ladha et al., 2020). The application rate was based on the Abuja convection of digestate application rate in Africa. The digestate was obtained from local farmer in UK and commercial digestate producers from Ghana (Safisana).

The digestates and the fertilising materials were characterised and tested on early growth of tomato plants, soils only through and incubation experiment and soil plants and water interactions. Application rate was based on regular usage of fertiliser application in most SSA countries. We found out that application of digestate can be comparable to mineral fertiliser usage. Application of the digestate was based on the total nitrogen content rather than the available Nitrogen (NH_4^+-N). Nitrogen being a limited plant and soil nutrient particularly in SSA Africa. Most institutions can test contents of the digestate. Testing such as Total nitrogen could be used as a means of digestate application. We adopted an application rate considering MOFA, Ghana and that of the UN/Abuja declaration for optimal fertiliser application in SSA. Soils were sourced from Ghana and characterised and the results were compared to find an equivalent soil related to the UK soil that can be used. Due to logistical constraints with land space and time, three experiments were conducted to look at how particularly digestate nutrients can support and interact with the soil over time. Time considered were 6 weeks, 6 months, and 3 months for each of the experiments respectively. Both soil types were worked on, and results presented. Due to the limited time involved in PhD only Nitrogen, and some forms of P and C were looked at. In the future with this level of research others might look at the other nutrients in the digestate with its interactions with the soil. Again, information of digestate and soil characterisation will inform farmers and researchers in SSA. The results of the investigations are important because digestate usage is new to SSA, hence can contribute to policy briefing and inform local farmers, researchers on the benefits and suitability of AD digestate as a fertilising material (García-Sánchez et al., 2015).

The reintroduction of AD elements particularly digestate onto the field to help in natural cycle is essential in closing the loop of the CE and the last element of the waste management system (Figure 1.1) (Chojnacka & Moustakas, 2024). The AD digestates selected in the Recirculate Project were not certified by BSI PAS 110:2014, but standard protocols were taken into consideration for its selection and based on practical usage by farmers in the UK and Ghana. Most of the analyses were conducted in the Lancaster Environment Centre's laboratory. Some analyses were done externally in the laboratories of the University of Ghana and the NRM in the UK. Results are genuine and considered standard methods.

1.10 Novelties of this Research thesis

Before this research thesis, the use of AD digestate had been used in agriculture and as soil conditioners in the literature from several points of view as follows:

1. Use as digestate as organic fertiliser - Digestate is rich in nutrients, especially nitrogen, phosphorus, and potassium. Research is ongoing in SSA to evaluate its potential as a bio-fertiliser, considering local soil conditions and crop varieties. (Smith et al, 2014; Schader, 2023)
2. Pathogen Reduction - Ensuring that digestate is free from pathogens is vital, especially when used on food crops. Studies have been conducted to understand and optimise pathogen reduction in SSA's AD processes (Avery et al., 2014),

3. Economic Models - For the uptake of AD technologies and the use of digestate products in SSA, robust economic models are essential. Various researchers have delved into the cost-effectiveness of Anaerobic digestion process and digestate utilisation in the region (Smith and Avery, 2014; Gebreegziabher, 2014, Orskov et al., 2014; Kebede et al., 2016)
4. Integration with Traditional Farming Practices - Understanding how organic sources of fertilisers (digestate) products can be integrated with traditional farming practices in SSA is crucial for their acceptance and adoption (Kim et al., 2021).

1.11 Gaps in Research on Anaerobic Digestion (AD) Digestate Use in Sub-Saharan Africa

Anaerobic digestion (AD) has emerged as a promising technology for waste management and RE production. While significant strides have been made in understanding and utilising AD digestate in the developed world, several critical aspects of digestate use remain under-researched in SSA. Identifying these gaps is essential for advancing sustainable agricultural practices and environmental management in the region.

1. Environmental Impact Assessments - Comprehensive studies on the environmental impact of digestate use in SSA are conspicuously lacking. In developed countries, extensive research has been conducted on nutrient leaching, greenhouse gas emissions, and overall ecological footprint of digestate application (Cattin et al., 2021). SSA needs tailored research to understand and

mitigate potential environmental impacts, particularly concerning nutrient leaching into water bodies (Lamolinara et al., 2023).

2. Digestate Processing Innovations - Unlike the developed world, where advanced technologies for digestate processing are being increasingly implemented, SSA lacks extensive research on converting digestate into more manageable forms like pellets or powders. This gap is significant given the transportation and storage challenges in the region. Developing cost-effective and efficient digestate processing methods suitable for SSA's unique context could revolutionise organic waste management and fertiliser use (Lamolinara et al., 2023).
3. Local Acceptance and Social Implications - Understanding local perceptions and social implications of digestate use is crucial for its successful integration into existing agricultural practices. While the developed world has explored the socio-cultural dimensions of AD technology, similar studies are sparse in SSA. Research should focus on community engagement, cultural considerations, and societal impacts to ensure that digestate use is not only agronomically viable but also socially accepted (Lamolinara et al., 2023).
4. Technological Innovations for Local Contexts - The evolution of AD technology in the developed world includes advancements in digestate handling, processing, and utilisation. However, SSA lags in researching region-specific technological solutions that address local challenges such as climate variability, infrastructure limitations, and resource availability. Innovations tailored to the local context could significantly enhance the efficiency and adoption of AD technologies in SSA (Saveyn and Eder, 2014; Logan, and Visvanathan, 2019).

5. Policy and Regulation Frameworks - Effective policy and regulation are vital for the wider acceptance and sustainable use of digestate products. While the developed world has established comprehensive frameworks governing AD operations and digestate use, similar policy-oriented research is relatively abscent in SSA. Investigating how to frame and implement policies that support digestate utilisation, considering SSA's unique socio-economic and environmental landscapes, is crucial (Lamolinara et al., 2023; Saveyn and Eder, 2014; Ndambi et al., 2019; Ghimire, 2013).

1.12 Thesis aims and objectives

The aim of this thesis is to provide new research evidence to support improved utilisation of digestate from AD within soil and agricultural systems. More specifically, the thesis focusses on understanding how the application of digestate impact plant growth, soil interactions and transformation on low nutrient sandy soils with pH lower than 7, sourced from Ghana and United Kingdom and their interactions and influences on soil C, N and P and their microbial communities and the risk of N leaching from pots experiment. To achieve the aim of the thesis, the following five chapters and associated objectives were developed:

1. Extensively explore and evaluate the resource recovery from waste streams in SSA including methods, technologies, and existing policies of waste safety, as well as the environmental impact, and socio-economic implications of recovered fertilisers (Chapter 2).

2. Evaluate the feasibility of replacing chemical fertilisers with digestate from different sources (Ghana and UK) using the micro-Tom tomato cultivar in sandy Podzols through a growth experiment (Chapter 3).

3. Evaluate how different doses of digestate (ranging from 22.5 to 90 kg N/ha) affect nutrient (N and P) cycling in two distinct soil types, namely sandy podzols and Ferric Acrisol through (i) the monitoring of pysio-chemical properties and microbial biomass (ii) determine the optimal digestate application rate for balanced nutrient cycling in different soil environments (Chapter 4).

4. Study (i) the effects of digestate application (based on a total N dose of 90Kg N/ha) under two different irrigation regimes on the growth and yield of micro-Tom tomatoes. (ii) Compare these effects with those observed in plants grown with urea and in unamended soil, considering the soil under planted and unplanted conditions. c. Assess water-use efficiency and yield quality under varying conditions of nutrient and water availability (Chapter 5).

The objectives of this final chapter in this thesis were to provide a broader synthesis and discussion of the outcomes of the primary research chapters reported earlier in the thesis, to consider the potential practical implications of the research outcomes for the management of digestate in agriculture, and to examine future research needs in the broad context of this thesis (Chapter 6).

1.13 Structure of the thesis

Chapter 1 is an introduction to the PhD research which gives the background to the research topic and sets out the rationale for the research, outlining the novelty, aim and objectives, and the structure of the thesis.

Chapter 2 is a literature review section that is focused on the recovery of resources from human faecal, food, and animal waste streams, focusing on the production of safe and sustainable fertilisers. The section evaluates the methodologies, efficiencies, and safety aspects involved in transforming these waste streams into usable fertilisers. The chapter also identifies the gaps in current research, and waste resources in SSA, highlighting some policies and suggesting potential areas for future studies.

Chapter 3 assesses the fertilising property of four (4) anaerobic digestates sources and urea mineral fertiliser on early growth and development of micro-Tom tomato cultivar. An experimental study of digestate as a soil fertiliser compared with chemical fertiliser using topsoil sourced from the UK with pH of 6.0 from Cheshire forestry commission. The chapter investigates the effect of digestate on plant productivity (morphological and above ground biomass) and soil properties such as EC, pH and available nitrogen upon addition of fertilising material and employed a statistical analysis to identify which fertilising material improves plant growth.   This chapter addressed Objective 2.

Chapter 4 explores the impact of digestate amendments on soil, focusing on how they affect the transformation and cycling of key nutrients (carbon, nitrogen, and phosphorus) and various soil properties. The study conducts incubation experiments using soils from Ghana and the UK, combined with different types of digestate, to assess changes in microbial biomass, community composition, electrical conductivity, pH, and other physicochemical properties. Additionally, it investigates the influence of these amendments on soil greenhouse gas emissions (CO_2, CH_4, and N_2O). The experiments also consider climate factors (moisture and temperature) and different doses of amendments over a 90-day period. This chapter aims to address a specific research objective (Objective 3) by providing experimental data on the effects of digestate on soil health and nutrient dynamics.

Chapter 5 evaluates the effects of digestate and irrigation on the growth and yield of micro-Tom tomatoes. The study used pots in controlled conditions in the glasshouse to study the impacts of two irrigation regimes effect on soil nutrient leaching and retention in planted and unplanted soils and to study the impacts of these effects on planted soils. This chapter addressed Objective 3.

Chapter 6 provides a summary and discussion of the key results found in the experimental and analytical chapters of this thesis which reflects on the current research, discusses its wider impacts, and makes recommendations for future research and draws remarks from each of the previous chapters of the thesis, concludes and makes recommendations for future work.

1.14 Statement of Authorship

This thesis has been prepared as a set of papers intended for submission to peer-reviewed journals. The chapters are presented in the format of the papers intended for submission to journals. Each paper's reference list is found in a combined reference list at the end of the thesis.

Chapter 1 provides a general introduction of the research area and the aims, objectives, and key hypotheses of the thesis. It is not intended for publication.

Chapter 2 Literature review intended for publication. Agyabeng Fofie E., Ghandi B. P., Ottite V. S., Lag-Brotons, A.J., Boateng A.F, Ezemonye L., Dodd I., Martin A.D. and Semple, K.T. Resource recovery from waste: producing safe and sustainable fertiliser from organic waste streams in Sub-Saharan Africa – A Review.

Intended journal - intended Waste Management

Chapter 3 is intended for publication. Agyabeng Fofie E., Ghandi B. P., Ottite V. S., Lag-Brotons, A.J., Boateng A.F, Ezemonye L., Dodd I., Martin A.D. and Semple, K.T. Effects of Digestate additions on the cycling of Carbon, Nitrogen, and phosphorus in soils. Intended journal - Bioresource Technology

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Chapter 5 intended for publication in Effect of different water application rate on micro-Tom treated with Digestate and mineral fertiliser. Agyabeng Fofie E., Ghandi B. P., Ottite V. S., Lag-Brotons, A.J., Boateng A.F, Ezemonye L., Dodd I., Martin A.D. and Semple, K.T.

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1.15 Contribution to Peer Reviewed Journal Articles during the PhD

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2. Bhushan P. Gandhi, Saanu Victoria Otite, **Esther A. Fofie**, Alfonso José Lag-Brotons, Lawrence I. Ezemonye, Kirk T. Semple, Alastair D. Martin, Kinetic investigations into the effect of inoculum to substrate ratio on batch anaerobic digestion of simulated food waste, Renewable Energy, Volume 195, 2022, Pages 311-321, ISSN 0960-1481,https://doi.org/10.1016/j.renene.2022.05.134.

2 Chapter Resource recovery from waste: producing safe and sustainable fertiliser from organic waste streams in Sub-Saharan Africa – A Review

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Abstract

This chapter reviews the comprehensive strategies for resource recovery from organic waste in Sub-Saharan Africa (SSA), focusing on the production of safe and sustainable fertilisers. Given SSA's unique challenges such as high organic waste output, rapid urbanisation, and inadequate waste management infrastructures, the chapter delves into various sustainable technologies and methods for waste recovery, including anaerobic digestion, composting, vermicomposting, pyrolysis, and nutrient extraction processes. These technologies not only mitigate environmental impacts but also enhance agricultural productivity by returning valuable nutrients to the soil. The chapter evaluates the safety and quality of recovered fertilisers, addressing potential contaminants and the effectiveness of various sanitisation treatments to ensure that these fertilisers are safe for agricultural use. Furthermore, it explores the economic implications of resource recovery, analysing cost-benefit dynamics and market trends that influence the viability and scalability of waste-to-fertiliser initiatives. The chapter also discusses the social, cultural, and policy frameworks that shape the adoption and success of these practices in SSA. By providing a detailed examination of current practices, technological innovations, and future directions, this chapter contributes to the ongoing discourse on sustainable waste management and the promotion of circular economy practices in the region.

2.1 Introduction

Sub-Saharan Africa (SSA) is characterised by a vast array of countries, ecosystems, and cultures (Onu et al., 2023; Zyl et al., 2023). In this diverse region, the traditional Linear economy (LE) approach, where raw materials are processed into products that are used until they are discarded as non-recyclable waste, effectively ending their lifecycle (Figure 2.1) (Sondh et al., 2024). Because most SSA economies practice the LE model, the region has witnessed significant changes in waste generation patterns and management strategies due to urbanisation, population growth, and shifts in lifestyle and consumption patterns (Etuah et al., 2023).

Approximately 57% of the region's waste is organic (Figure 2.2), stemming from food and agriculture, urbanisation, population growth, and changes in dietary patterns (Rubagumya et al., 2023). The predominance of agrarian societies in SSA leads to the generation of substantial crop residues, yard, and green waste, which are often left to decay or are incinerated, contributing to environmental pollution and health hazards (Renard, 1997; Ibrahim, 2020). The challenge is compounded by rapid urbanisation and the adoption of convenience-oriented products, which mark a transition from traditional and sustainable practices to more consumer-driven lifestyles, further exacerbating food loss and waste generation (Saketa, 2023; Szabo, 2016; Sheahan and Barrett, 2017). Moreover, livestock farming adds significant amounts of animal waste, and in many parts of SSA, inadequate sanitation facilities contribute to the generation of substantial human waste.

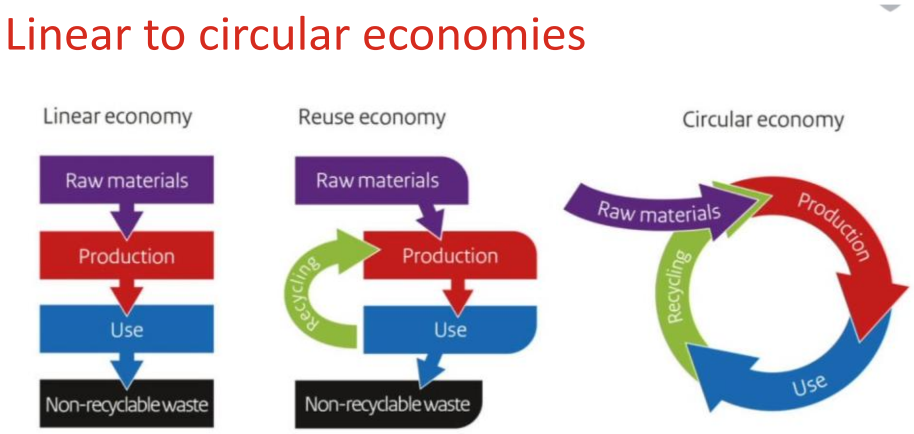

Figure 2.1 Linear to Circular Economies (Govermnent.nl, 2024)

Despite the vast potential for resource recovery, less than 1% of municipal solid waste (MSW) undergoes composting (Couth and Trois, 2012; Olanrewaju, 2020), with the majority being unsustainably dumped or burned (Kaza et al., 2018). This not only results in lost resources but also incurs significant economic costs to countries within SSA, amounting to losses equivalent to 0.9% to 2% of each country's GDP annually due to improper waste disposal (WSP, 2012). In response to these challenges, composting emerges as a prevalent waste management method in rural areas, although systematic and scaled-up initiatives are required for effective organic waste management (Modupe et al., 2020). The limited reach and impact of large-scale recycling of organic waste into valuable products such as biogas or organic fertilisers highlight the need for enhanced resource recovery strategies (Atelga et al., 2020).

The expected rise in waste generation, potentially reaching 244 million tons by 2025 alongside a projected population of about 1.50 billion (UN, 2022; Ayeleru, 2020), presents both a significant challenge and an opportunity for resource recovery.

The Reuse Economy model (Figure 2.1) introduces an element of sustainability by allowing for the reuse of products. After the use phase, instead of becoming waste, products or their components might be reused, which somewhat reduces the intake of new raw materials and the generation of waste (Martínez-Fernández, et al., 2013). However, products that cannot be reused still end up as non-recyclable waste. Organic wastes are rich in essential nutrients for plant growth, and their recovery and reuse could greatly reduce the demand for synthetic fertilisers (Orner et al., 2021). Although the study of resource recovery has gained traction in the developed world, SSA faces numerous challenges in adopting effective waste management technologies and policies. This review aims to synthesize the literature on resource recovery in SSA, providing an in-depth overview of existing knowledge, analysing research trends, identifying gaps, and proposing areas for future research that could enhance the understanding and efficiency of resource recovery strategies in the region.

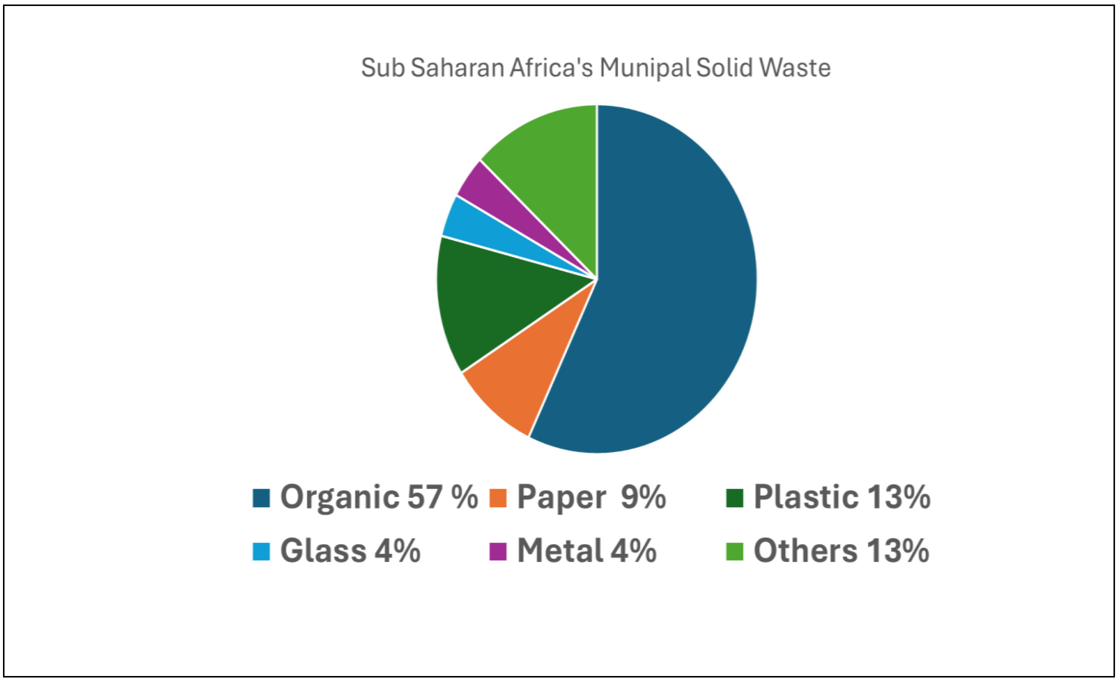

Figure 2.2: The state of waste in Africa (UNEP, 2018)

2.2 Methods and Technologies for Resource Recovery

The circular economy involves not only the reuse of products but also their recycling is the most sustainable model compared to linear and re-use economy model (Figure 2.1). This creates a closed loop system where raw materials are used to produce goods, the goods are used, and then all materials are recycled back into production. This model minimises waste significantly, maximizes the value extracted from resources, and greatly reduces the environmental impact by continually cycling materials. The urgency for sustainable waste management and resource recovery is intensifying with the increasing rates of waste generation and the environmental challenges that accompany it. Techniques such as anaerobic digestion (Ghandi et al., 2022), composting (Couth & Trois, 2012) and vermicomposting (Enebe & Erasmus, 2023), pyrolysis and biochar production (Mehta et al., 2022), as well as nutrient extraction and solubilisation processes (Chojnacka et al., 2022), are emerging as promising technologies for organic waste resource recovery due to their ability to reuse either main products or their by-products.

2.2.1 Anaerobic Digestion and Biogas Production

Anaerobic digestion (AD) is a biological process in which microorganisms break down organic materials in an oxygen-free environment (Ghandi et al., 2022). The AD process (Figure 1.2) yields biogas consisting of a mixture of methane and carbon dioxide and a nutrient-rich by-product known as digestate. This process provides a controlled source of renewable energy, reducing greenhouse gas (GHG) emissions while producing digestate that serves as an excellent soil amendment. It is estimated that Sub-Saharan

Africa's (SSA) organic waste has the potential to generate approximately 12.8 billion m^3 of biogas annually, equating to 133 million GWh of energy (Rupf and Boer, 2015), along with a substantial volume of digestate usable in agriculture.

The AD process is suitable for a wide range of biodegradable materials (Figure 2.4), provided they are in suitable ratios for optimal microbial activity. For example, agricultural residues, food waste, and animal manure can all be effectively processed through AD (Chen et al., 2010). Utilising digestate to support plant growth and enhance soil fertility embodies the principles of a circular economy, where all outputs are viewed as resources, minimising waste (Ammenberg & Roozbeh, 2017).

Koszel and Lorencowicz (2015) suggest that considering its physicochemical properties, digestate should primarily be used as a bio-fertiliser. The high nutrient content of digestate makes it particularly valuable in agricultural applications, promoting sustainable farming practices. For instance, digestate has been shown to improve soil structure, increase water retention, and provide essential nutrients to crops (Tambone et al., 2010).

Further advancements in AD technology have enabled the co-digestion of various organic waste streams, optimising biogas production and nutrient recovery. For example, the integration of food waste with agricultural residues has been found to enhance biogas yields due to the complementary nutrient profiles of these substrates (Zhang et al., 2013). Additionally, the development of pre-treatment methods, such as thermal hydrolysis, has improved the efficiency of the AD process by breaking down complex organic molecules, making them more accessible to microorganisms (Carrere et al., 2016).

AD therefore is a versatile and efficient technology for resource recovery, transforming organic waste into renewable energy and valuable bio-fertiliser, thereby supporting sustainable agricultural practices and contributing to the circular economy.

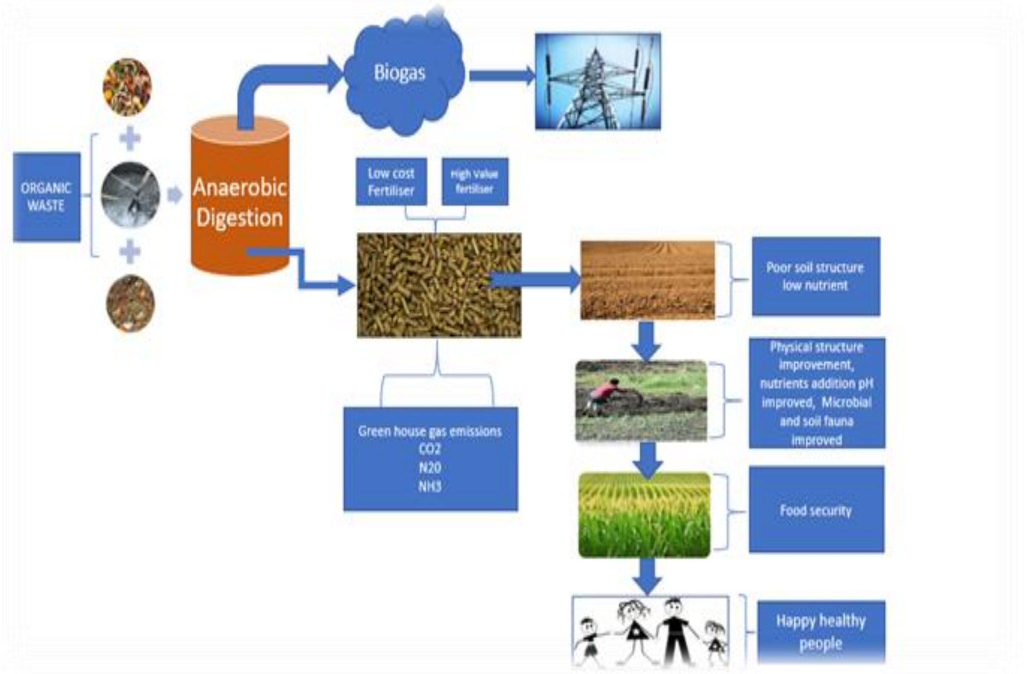

Figure 2.3 The benefits of resource recovery from waste and its potential impact on sustainability.

2.2.2 Composting

Composting, the aerobic microbial decomposition of organic materials such as plant residues and food scraps (Modupe et al., 2020; Nikema et al., 2014), is particularly important in Africa due to the continent's pressing needs for sustainable waste management and agricultural productivity improvement. In many African countries, the practice of composting is gaining traction not only as a waste reduction strategy but also to enhance food security by improving soil quality.

In regions across Africa, composting methods vary widely, often adapted to local conditions and available resources. For example, in urban areas of East Africa, small-scale composting initiatives have been implemented in households to manage organic waste, reducing reliance on inadequate municipal waste services (Nkematu et al., 2018). Rural communities, on the other hand, typically engage in larger scale composting practices, often integrating these systems with traditional farming practices to maximise land productivity (Ogunwande et al., 2014).

Despite its benefits, composting in Africa faces several challenges. These include a lack of awareness about the composting process, minimal governmental support, and inadequate access to the necessary tools and knowledge for efficient composting (Modupe et al., 2020). However, these challenges also present opportunities for development. For instance, educational programs aimed at farmers can emphasise the dual benefits of waste reduction and soil enhancement. Additionally, government policies supporting composting can help scale up these practices, turning organic waste from a liability into a valuable resource.

The compost process (Figure 2.3) creates rich humus that adds essential nutrients back into the soil, improving its structure and water retention capabilities (Sheahan and Barrett, 2017). This is critical in areas suffering from soil degradation and erosion. Moreover, the application of compost can reduce the need for chemical fertilisers, which are often expensive and environmentally damaging.

Composting significantly contributes to soil fertility in African agriculture (Figure 2.4). Again, compost application significantly enhanced plant growth metrics and maize yield in SSA (Amoding et al., 2011). In the broader context of climate change mitigation, composting offers a practical approach to carbon sequestration in Africa (Couth & Trois, 2012). By diverting organic materials from landfills, where they would decompose anaerobically and produce methane, composting allows for the carbon in organic waste to be stabilised and stored in the soil, thus reducing GHG emissions (Nikema et al., 2014).

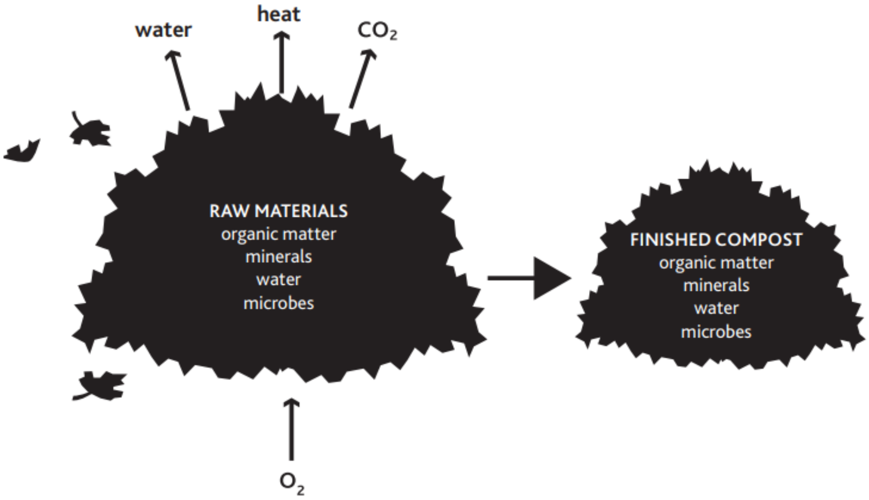

Figure 2. The composting process (Chen et al., 2011).

2.2.3 Vermicomposting

Vermicomposting utilises specific species of earthworms, like the red wiggler worm (Eisenia fetida), to break down organic materials (Komakech et al., 2016). The worms' castings are a highly nutritious organic fertiliser, which is known to control greenhouse gas emissions from agricultural soils, unlike inorganic fertilisers which can increase them (Enebe and Erasmus, 2023). Vermicomposting is faster than traditional composting, produces high-quality fertiliser, and is scalable for small operations. In

Uganda, vermicompost studies have demonstrated a material reduction rate of 45.9%, a waste-to-biomass conversion rate of 3.5%, and a return on investment of 275% when treating about half a ton of cow manure (Komakech et al., 2016). In non-African settings, vermicompost has demonstrated significant advantages, bringing about average increases of 26% in commercial yield, 13% in total biomass, 78% in shoot biomass, and 57% in root biomass (Blouin et al., 2019). These impressive results highlight the potential of vermicomposting as a sustainable waste management solution that can enhance agricultural productivity and economic returns that can be applied in a SSA context.

2.2.4 Pyrolysis and Biochar Production

Pyrolysis is a process that thermally decomposes organic materials at high temperatures in the absence of oxygen, resulting in the production of bio-oil, syngas, and biochar. Biochar, a carbon-rich and porous material, is particularly beneficial for soil health and environmental sustainability. Biochar’s application in agriculture has been shown to significantly improve soil fertility and water retention. Moreover, biochar is recognised for its ability to sequester carbon, thereby contributing to climate change mitigation (Fagbohungbe et al., 2017; Christou et al., 2022; Okebalama and Marschner, 2023).

Research has demonstrated that biochar can effectively reduce the leaching of essential nutrients such as nitrogen and phosphorus, which not only enhances soil nutrient content but also decreases the volume of leachate, minimising potential groundwater contamination (Akinnuoye-Adelabu et al., 2019). For example, in a study by Lehmann et al. (2011), biochar application in agricultural fields resulted in a substantial decrease in nitrogen leaching by up to 50%, while another study by Biederman and Harpole (2013) showed increased crop yields due to improved nutrient availability. These findings underscore the multifaceted benefits of biochar in sustainable agricultural practices and environmental conservation.

2.2.4 Nutrient Extraction and Solubilisation Processes

Nutrient extraction and solubilisation processes encompass a range of techniques designed to extract and solubilise nutrients, thereby enhancing their availability for plant uptake (Li et al., 2019a; Chojnacka et al., 2022). These technologies primarily focus on converting nutrients from organic waste streams, such as agricultural residues and food waste, into more accessible forms or concentrating them for use as fertilisers. By doing so, these methods reduce the reliance on mineral fertilisers and facilitate the recycling of essential nutrients, thereby promoting sustainable agricultural practices (Vingerhoets et al., 2023; Chojnacka et al., 2022). For instance, anaerobic digestion is a widely used technique that breaks down organic material in the absence of oxygen, producing biogas and a nutrient-rich digestate. This digestate can be further processed to extract valuable nutrients like nitrogen and phosphorus (Tambone et al., 2010). Another example is the use of acid or base hydrolysis to solubilise nutrients from organic matter, making them readily available for plant uptake (Möller and Müller, 2012).

In addition to these methods, recent advancements in biotechnological processes, such as the use of microbial consortia to enhance nutrient solubilisation, have shown promising results. For example, the application of specific bacterial strains has been demonstrated to improve phosphorus solubilisation from rock phosphate, which can be used as an alternative to traditional phosphorus fertilisers (Alori et al., 2017). Furthermore, enzymatic treatments have been developed to break down complex organic molecules in waste streams, releasing nutrients in a form that plants can readily absorb (Singh et al., 2014).

Overall, these nutrient extraction and solubilisation processes not only improve the efficiency of nutrient use in agriculture but also contribute to the reduction of environmental pollution associated with excessive fertiliser application. By integrating these techniques into agricultural systems, it is possible to achieve more sustainable and environmentally friendly farming practices.

2.3 Safety and Quality of Recovered Fertilisers

Recovered fertilisers from organic waste streams have considerable potential to advance sustainable agricultural practices (Chojnacka et al., 2022). Nevertheless, ensuring their safety and quality is imperative to avoid adverse effects on human health and the environment. A comprehensive assessment of potential contaminants, including pathogens, heavy metals, and chemical residues, is necessary. This section explores the effective methods for the treatment and sanitisation of these fertilisers, thereby maximising their benefits in sustainable agriculture.

2.3.1 Possible Contaminants

Organic fertilisers recovered from waste streams may contain pathogens, heavy metals, and pesticide residues. Notably, waste derived from human and animal by-products could harbour harmful bacteria (e.g., E. coli, Salmonella, Faecal Enterococci), viruses, and parasites, presenting health risks if transferred from crops to consumers (Kebalo et al., 2024; K. Chojnacka et al., 2022). Studies such as those by Lalander et al. (2015) reported low pathogen reduction in vermicompost, while Kebalo et al. (2024) noted the presence of Faecal Enterococci in lettuce cultivated with recovered fertilisers. Heavy metals like lead, cadmium, arsenic, and mercury can accumulate in the soil, posing long-term risks to the ecosystem and human health. In addition, wastes, especially those from urban sources or medicated livestock, may contain organic pollutants such as pharmaceutical compounds and pesticides (Baguma et al., 2023).

2.3.2 Treatment and Sanitisation Processes

Effective treatment and sanitisation processes can safeguard the quality of organic fertilisers, ensuring their safety for land application. Techniques like thermal, chemical, biological treatments, and UV radiation have been proven to reduce contaminant levels (Nikema et al., 2014; Chojnacka et al., 2022). Heat treatments, such as composting and pyrolysis, effectively eradicate pathogens. The addition of lime can increase pH levels, which is detrimental to many pathogens and can degrade some organic contaminants. Beneficial microbes in compost can also inhibit pathogens, and composting can facilitate the breakdown of antibiotics in organic wastes (Ren et al., 2021; Chojnacka et al., 2022). Furthermore, earthworms in vermicomposting systems can contribute to pathogen reduction. UV exposure is another effective disinfection method for liquid wastes, while controlled digestion processes can mitigate pathogen levels in organic wastes. Recent research involving the fungus Myrothecium verrucaria indicates promising biocontrol capabilities, potentially improving the biological safety of anaerobic digestates (Pengjiao et al., 2023).

2.3.3 Standards and Guidelines for Safe Fertiliser Application

Compliance with established standards and guidelines is crucial for ensuring the application of organic fertilisers is safe for both human and environmental health (Kebalo et al., 2024). Regulations vary by country and region, outlining permissible contaminant levels in fertilisers (Bidzakin et al., 2023). International organisations, such as the WHO, offer guidelines for the safe use of wastewater, sludge, and excreta in agriculture (FAO, 2023; WHO, 2013), often including recommendations for application rates that prevent unsafe accumulation of contaminants. Guidelines may advise against certain crops with recovered fertilisers, particularly if they pose a higher pathogen risk, and suggest waiting periods between fertiliser application and harvesting to minimise consumer exposure (Kebalo et al., 2024).

In the UK, the Publicly Available Specification (PAS) 110 provides a comprehensive framework to produce digestate. PAS 110 ensures that digestate derived from anaerobic digestion processes meets stringent quality criteria, including limits on pathogens, heavy metals, and physical contaminants. Compliance with PAS 110 not only guarantees the safety and quality of digestate but also facilitates its acceptance and use in agriculture (British Standards Institution, 2014).

In Africa, there are no continent-wide standardised regulations equivalent to the UK's PAS 110 for organic fertilisers. However, various countries have developed or are in the process of developing their own standards and guidelines for organic fertilisers:

a. Kenya: The Kenya Bureau of Standards (KEBS, 2011) has developed standards for organic fertilisers, including KS 2214:2010, which outlines the specifications for compost manure.
b. South Africa: The Department of Agriculture, Forestry and Fisheries (DAFF, 2012) regulates the quality and safety of fertilisers, including organic ones, requiring registration and testing to ensure safety.
c. Ghana: The Ghana Standards Authority (GSA, 2018) has developed standards for organic fertilisers to promote sustainable agriculture.
d. Nigeria: AOAPN (2018) Association of Organic Agriculture Practitioners of Nigeria has developed standards for organic agriculture for use by its members and farmers.
e. East African Community: The EAC (2008) is harmonising standards for various agricultural inputs, including fertilisers, through the East African Standards (EAS) framework.

Through the Comprehensive Africa Agriculture Development Programme (CAADP), the AU advocates for the development of harmonised standards for agricultural inputs across the continent to promote sustainable agriculture and improve food security.

While these efforts show progress, the development and enforcement of standardized regulations for organic fertilisers across Africa remain varied and are often in the early stages compared to established standards like the UK's PAS 110.

2.4 Economic Importance of Resource Recovery

2.4.1 Cost-Benefit Analysis of Different Recovery Methods

The conversion of organic waste into organic fertilisers not only presents significant environmental benefits but also creates substantial economic opportunities. This transformation catalyses the emergence of new industries and economic activities, offering a sustainable solution that can be both profitable and environmentally sound. Economic considerations are crucial when assessing the viability of various organic waste recovery methods. Initial investments differ significantly across technologies; for instance, large-scale anaerobic digesters require substantial capital due to their complex infrastructure, but they yield high returns through the production of both biogas and liquid digestate (Bond, & Templeton, 2011). Conversely, smaller-scale composting units, while less costly to establish, may offer lower financial returns due to the reduced volume of end products (Smith et al., 2001). Operational costs, including energy consumption, labour, maintenance, and daily operations, also vary markedly between technologies. For example, pyrolysis is an energy-intensive process compared to composting, which has minimal energy requirements but may involve higher labour costs (Smith et al., 2001). To illustrate, a study by Jones & Vale, (2009) demonstrates that medium-scale anaerobic digestion facilities can achieve break-even within five years, primarily through the sale of biogas and the use of digestate as a high-quality organic fertiliser.

2.4.2 Trends and Pricing Dynamics in the Organic Fertiliser Market

The bio-fertiliser market, currently valued at USD 2.3 billion, is forecasted to expand significantly, reaching USD 3.9 billion by 2025, with a Compound Annual Growth Rate (CAGR) of 11.6% (Kumar et al., 2022). This growth trajectory is primarily driven by an increasing global awareness of the harmful effects of synthetic chemicals on human health and the environment. A rising consumer inclination towards organic products is further fuelling the demand for organic agricultural practices worldwide. A variety of sources, such as compost, alfalfa meal, soybean meal, and seaweed extracts, are utilised to produce organic fertilisers, which are derived from plant, animal, and mineral by-products (GVR, 2023).

In SSA, the focus of reforms has been predominantly on macroeconomic adjustments aimed at improving agricultural price incentives. However, these reforms have largely neglected the non-price factors essential for farm-level decision-making. The scant attention paid to building institutional and technological support systems has impaired the transmission of macroeconomic reforms' price stimuli, especially within the sector of non-tradable food crops, which are primarily cultivated for domestic consumption (Mensah-Bonsu, 2010).

A comparison of fertiliser consumption trends underscores the disparities between regions: Asia experienced a staggering 182% surge in fertiliser use from 1980 to 2000, while SSA reported a modest increase of only 16% over the same period. The sluggish adoption of modern inputs in Africa signifies lost opportunities to enhance agricultural productivity and incomes (Bumb and Baanante 2020; Jayne et al, 2003).

For meaningful advancements in productivity and income, it is critical to bolster the use of organic fertilisers to increase food production in SSA. There is a direct correlation between agricultural productivity growth and overall economic development, as well as poverty reduction (Tripathi et al., 2024). Thus, agricultural productivity acts as a catalyst for broad economic growth and development. It directly impacts the livelihoods of farmers, contributes to national food security, supports related industries, and underpins the socio-economic development necessary for poverty reduction. These elements are interlinked, creating a cycle where agricultural productivity supports economic development and poverty reduction, which in turn reinvests in and furthers agricultural productivity.

The pricing dynamics in the organic fertiliser market are affected by multiple factors. Consumer perceptions regarding the efficacy, safety, and environmental footprint of organic fertilisers play a pivotal role in market valuation and can lead to premium pricing. The shift towards sustainable farming methods has heightened the demand for these fertilisers, particularly in locales devoted to eco-friendly farming practices. Market volatility, including fluctuations in the cost and availability of synthetic fertilisers, often positions organic options favourably. Additionally, branding and marketing strategies that effectively communicate the advantages of organic over conventional fertilisers contribute to shaping market dynamics. Hameed et al. (2017) note that the marketed environmental benefits of organic fertilisers have the potential to garner higher prices in the market.

2.4.3 Economic Incentives for Waste-to-Fertiliser Ventures

Governments play a pivotal role in promoting the development of waste-to-fertiliser industries through various incentives. These incentives can include tax reliefs, subsidies, and grants aimed at reducing the financial risks associated with pioneering green enterprises. For instance, Carr et al. (2019) highlight how regulatory support, coupled with economic incentives, can encourage private investment in waste valorisation projects. Partnerships between the public and private sectors are essential for pooling resources and expertise, thus enhancing the financial feasibility of these ventures. Additionally, these projects can benefit from participating in carbon markets or obtaining green certifications, which provide further financial incentives. Supporting training programs to equip local entrepreneurs and farmers with the necessary skills for managing waste-to-fertiliser operations is another crucial aspect of government and NGO involvement.

This comprehensive approach not only underscores the significant economic impact of resource recovery ventures but also aligns with global sustainability objectives, making a compelling case for increased investment and support in the organic fertiliser sector.

2.5 Environmental and Sustainability Impacts

The transformation of organic waste into organic fertilisers plays a pivotal role not just economically but also in terms of environmental health and sustainability (Rajkhowa et al., 2019). The environmental footprint of this conversion process affects everything from waste management practices to the health of agricultural soil. Key to mitigating environmental and sustainability impacts is the reduction of landfill waste and associated greenhouse gas emissions, alongside comprehensive life cycle assessments of organic waste recovery processes to gauge their influence on soil health and biodiversity.

2.5.1 Reduction in Waste Landfilling and Associated Greenhouse Gas Emissions

A significant portion of generated waste ends up in landfills, leading to considerable environmental pollution when mismanaged (Igbum et al., 2019). Diverting waste from landfills and processing it through aerobic methods or methane capture via anaerobic digestion can significantly lower these emissions. Transforming organic waste into fertilisers reduces landfill waste, preserves land, mitigates the need for new landfill sites, and curtails environmental degradation (Igbum et al., 2019). Moreover, this practice enhances soil organic matter and curbs greenhouse gas emissions, thereby contributing to global warming mitigation and climate change adaptation (Beesigamukama et al., 2023; Rajkhowa et al., 2019).

2.5.2 Life Cycle Assessment of Organic Waste Recovery Processes

Life Cycle Assessment (LCA) is a tool that quantifies the environmental impacts associated with all stages of a product's life from procurement to disposal (Hussein et al., 2023). Within the scope of organic waste recovery, LCA scrutinises the environmental pros and cons across various strategies. It evaluates the entirety of the waste-to-fertiliser conversion process, including collection, processing, and application, as well as energy and water use. LCAs illuminate greenhouse gas emissions and pollutants at each recovery stage, aiding in the optimisation and comparison of methods. They also examine the ultimate effects of fertilisers on soil, such as nutrient leaching and long-term sustainability. Martinez-Blanco et al. (2009) utilised LCA to evaluate the environmental impact of compost use in tomato cultivation compared to mineral fertilisers, noting that the production of compost was the most impactful stage. However, agricultural production and quality showed no significant difference between compost and mineral fertiliser use. Another study by Yu and Li (2021) determined that anaerobic digestion of sorted municipal solid waste, as opposed to incineration, could reduce carbon emissions by 10.6% and save 4% of cumulative energy demand.

2.5.3 Impact on Soil Health and Biodiversity

Integrating organic fertilisers into soil can significantly enhance its structure, augment water retention, and facilitate crop growth, thus reducing soil erosion and runoff (Romero et al., 2021). The introduction of organic matter promotes microbial activity, fostering healthier and more resilient soils as these microorganisms are crucial for nutrient cycling, decomposition, and disease suppression. Consequently, soil ecosystem health is intrinsically tied to the broader biodiversity and ecological systems' vitality (Xiu et al., 2019). The utilisation of recovered organic fertilisers may also diminish reliance on mineral fertilisers, which can cause soil acidification and hazardous nutrient runoff into aquatic ecosystems if overused (Chojnacka et al., 2020; Romero et al., 2021).

2.6 Social and Cultural Perspectives of Recovered Organic Fertilisers in SSA

2.6.1 Perceptions and Acceptance of Waste-Derived Fertilisers in SSA

The transformation of organic waste into fertilisers and their subsequent integration into the agricultural ecosystems of SSA is harmonious with the region's socio-cultural principles. Historically, communities in SSA countries, including Burkina Faso, Ghana, and Nigeria, have embraced the use of organic manure on their lands (Smith et al., 2014; Lewcock, 1999). Nonetheless, certain types of waste, particularly human waste, may be viewed with scepticism and considered unsanitary (Moya et al., 2019). The challenge lies in overcoming the associated stigma and health concerns, which requires demonstrating the safety and effectiveness of waste-derived fertilisers convincingly. Farmers prioritise the fertilisers' performance and need evidence that organic alternatives can compete with or surpass traditional or mineral fertilisers.

Studies that compared long-term soil amendment effects of various organic fertilisers indicated notable variations in soil chemistry and biology, suggesting that organic amendments can alter soil microbial processes and enhance soil fertility differently than mineral fertilisers (Charlton et al., 2016; Odlare et al., 2008; Mantovi et al., 2005).

2.6.2 Training and Community Engagement for the Adoption of Recovered Organic Waste

Endorsing local influencers, such as successful farmers or esteemed community figures, can facilitate community buy-in. Observable demonstrations showcasing the benefits on crop yields and soil health can be more effective than verbal promotion alone. These initiatives should respect and incorporate local customs and traditions. An illustrative example is the outreach performed by the Recirculate project in SSA (GCRF-Recirculate, 2021).

2.6.3 Local Employment, Empowerment, and Gender Considerations

The waste-to-fertiliser sector in SSA promises job creation and opportunities for women's empowerment, though traditional norms may influence roles and resource access. Workforce development can span from organic farming to business administration. The sector's success hinges on its resonance with local values and social structures. The adoption of waste-derived fertilisers, particularly those from human excreta, encounters resistance, often rooted in cultural attitudes like faecophobia.

Models from countries like Vietnam and China, which have long-standing practices of using human waste in agriculture, could provide instructive case studies (AUDA-NEPAD, 2021).

Introducing recovered fertilisers involves navigating perceptions, and this can benefit from educational campaigns that address public apprehensions. The cost of transportation and potential subsidies play pivotal roles in the uptake of these fertilisers, underscoring the need for supportive frameworks, like public-private partnerships. Established assurance schemes from countries like the UK and USA could serve as templates for boosting consumer confidence in SSA's biosolid products (Davidson 2024).

2.7 Policy and Regulatory Framework in SSA

An effective policy and regulatory framework are pivotal for steering the success of any sector. This is particularly crucial for waste-to-fertiliser initiatives in SSA, where public health, agriculture, and environmental concerns converge.

2.7.1 Existing Policies on Waste Management and Fertiliser Application

Waste management regulations exist in many SSA countries, but they are often limited and urban-centric (Muheirwe et al., 2022). These policies typically stress waste reduction, segregation, and disposal, increasingly recognising waste as a valuable resource (Agbefe, 2019). While standards are established to ensure the safety and nutrient content of fertilisers, including those derived from waste, their application to waste-derived fertilisers may not be explicit.

The implementation of these policies is a challenge across SSA, with ineffective deterrents for illegal waste dumping, evidenced by modest fines in countries like South Africa (Polasi et al., 2020; Muheirwe et al., 2022). There is a gap between policy existence and the actual guiding and constraining of behaviour. In Nigeria and Uganda, for example, despite having environmental sustainability laws, enforcement is lax, resulting in widespread improper waste disposal (Muheirwe et al., 2022). However, countries like Rwanda and Swaziland exhibit improved solid waste management due to robust enforcement (CSE, 2017; Muheirwe et al., 2022). Rwanda's community driven 'Umuganda' initiative demonstrates the potential of policies that engage citizens actively (Baffoe et al., 2020).

A major impediment to policy implementation is the limited budget, which compromises the capacity of regulatory bodies. The Democratic Republic of Congo and Kenya, particularly, face financial constraints that hinder enforcement, especially in informal settlements (Muheirwe et al., 2022).

2.7.2 Potential Incentives for Promoting Waste-Derived Fertilisers

To encourage the production of waste-derived fertilisers, governments could offer tax reliefs or subsidies (Carr et al., 2019). Purchasing such fertilisers for state-led agricultural initiatives or public spaces can also signal governmental support. Additional measures, such as providing training and grants to sector businesses and

NGOs, can spur innovation and improve product quality. Education campaigns about the advantages of waste-derived fertilisers can bolster demand.

2.7.3 Regulatory Challenges and Gaps in Implementation

Regulatory challenges and gaps are prevalent in SSA. Ambiguities in regulations due to the lack of clear definitions for waste-derived fertilisers complicate compliance and enforcement (Chojnacka et al., 2022). Jurisdictional overlaps among agencies can also hamper regulation, as observed in Nigeria and Uganda. Progressive policies may exist, but their impact is often dulled by inadequate infrastructure for effective monitoring and enforcement. In Ghana, for instance, the informal nature of waste management and agriculture poses challenges for integrating these sectors into formal regulatory frameworks (Oteng-Ababio et al., 2023). Ensuring that waste-derived fertilisers conform to both local and international standards is also essential for global trade compliance.

2.8 Case Studies and Success Stories

In SSA, the field of converting waste to fertiliser has seen numerous innovative approaches that have provided valuable lessons and have positively impacted communities. Notable among success stories is Sanergy in Nairobi, Kenya. Sanergy has crafted a sustainable model to collect waste from the city's informal settlements, process it, and produce organic fertiliser (Peletz et al., 2020). This innovative solution not only addresses critical sanitation needs but also supplies local farmers with an affordable and efficient soil amendment.

Another noteworthy venture is Waste Enterprisers, Ghana, which has turned faecal sludge into biodiesel and organic fertiliser (SEED, 2010). By converting a public health concern into valuable commodities, they offer an economically viable solution to urban sanitation challenges. Other key waste to fertilisers in Ghana include Safisana Company limited and Zoom Lion company in Ghana.

2.8.1 Lessons Learned

The journey of Sanergy in Nairobi illustrates the multifaceted nature of waste-to-fertiliser initiatives (Peletz et al., 2020). Far beyond the scope of agriculture alone, these initiatives intersect crucially with urban sanitation, health, and the broader frame of community livelihoods. Embracing a holistic approach to the ecosystem, where waste management is integrated into a wider context, has proven to yield significant outcomes. A critical lesson from these experiences is the vital role of local context in shaping successful implementation strategies. What works in one area may not directly apply to another due to cultural, environmental, or socio-economic differences. For example, strategies that have shown promise in the urban landscapes of Ghana may necessitate adjustments to fit the characteristics of rural environments or areas with distinct attitudes toward waste management.

Furthermore, the importance of cooperation between different sectors cannot be overstated. The successful initiatives have demonstrated that the collaboration between local governments, entrepreneurs, and communities is not just beneficial but essential. This partnership fosters a conducive environment for innovation and sustainable growth, ensuring that projects are not only effective but also deeply rooted in the needs and aspirations of the community.

2.8.2 Scalability and Replicability in SSA

The economic feasibility of a project significantly impacts its scalability, particularly in the context of producing organic fertilisers and biogas (Böhm et al., 2020). Organic waste contains valuable nutrients that can enhance agricultural and farming practices by providing essential nutrients to crops such as vegetables and fruits (Maji et al 2020). Using low-energy processes like simple aerobic digestion, even at a household level, this organic waste can be converted into compost, which serves as a natural fertiliser to improve soil for agricultural and horticultural applications (Sharma et al., 2019). More sophisticated methods, such as anaerobic digestion, allow for the conversion of greater quantities of organic waste into fertilisers, as well as the generation of energy in the form of electricity and heat. Financial viability hinges on the ability of revenue streams from these products to not only cover operational and production costs but also to generate a profit. A study by Kalkanis et al., (2022) showed that compost (clear, organic without other fractions) per ton cost £308. This shows that compost can be profitable if made as a business in SSA.

Furthermore, government policies play a pivotal role in scaling these initiatives. Incentives aimed at supporting green businesses and promoting organic farming are instrumental in enhancing the economic viability and scalability of such projects (Kulin, & Johansson, 2019). Conversely, restrictive, or unclear regulations can stifle growth, underscoring the necessity for regulatory clarity and proactive governmental support. In addition to regulatory and financial aspects, market demand driven by awareness and education is critical. Enhancing farmer awareness regarding the benefits of organic fertilisers can substantially increase market demand, a crucial factor for the expansion of these projects (Liu & Liu, 2024; Xie et al., 2015). As projects scale, they may encounter varying waste characteristics and diverse agricultural requirements, necessitating adaptive technological processes. The ability to tailor technological solutions to these varied conditions is essential for the successful replication and expansion of organic fertiliser and biogas initiatives (Meinke et al., 2009; Liu & Liu, 2024).

The extensive array of waste-to-fertiliser projects in SSA serves as a valuable repository of experiences for both new enterprises and policymakers (Onu & Mbohwa, 2021). Analysing these success stories and understanding the factors contributing to their success, as well as the challenges they have overcome, reveals significant potential to expand their impact across the continent. Such expansion not only has the potential to transform waste management practices but also to revolutionize agricultural methods through a symbiotic relationship between waste management and agriculture (Lee et al., 2023).

2.9 Technical Challenges in Optimising Recovery Processes

The first challenge is varied composition of waste (Dronia et al., 2023). Organic waste streams, especially those from urban settings, can be heterogeneous in nature. This variability can make it challenging to achieve consistent output quality and nutrient content in the derived fertilisers (Dronia et al., 2023; Chojnacka et al., 2024). Again, ensuring that the fertilisers recovered are devoid of pathogens, heavy metals, or other contaminants is crucial. Achieving this level of safety might require advanced treatment processes, which can be resource intensive. Thirdly, not all waste processing methods can recover nutrients with the same efficiency. Research and innovation are needed to maximise the capture of valuable nutrients from diverse waste streams.

2.9.1 Logistical Challenges in Waste Collection and Distribution

Rapid urban growth in African cities has led to severe waste disposal problems. Increased population has put immense pressure on infrastructure and exacerbated unhygienic conditions in urban areas. In countries like Ghana, South Africa, Zambia, and Zimbabwe, waste issues, particularly with plastic bags, have become major environmental and aesthetic concerns (Aziale, & Asafo-Adjei, 2013).

In Ghana, cleanliness is traditionally valued only within one’s immediate environment, a legacy of colonial-era governance where sanitation was managed externally. There is a notable reluctance among educated individuals to pursue careers in waste management, often viewed as low-status or politically complicated roles. This contributes to a shortage of skilled personnel in the sector (Aziale, & Asafo-Adjei, 2013).

In many parts of SSA, the infrastructure for waste collection and transportation might be rudimentary. This can hinder the consistent and efficient gathering of organic waste, especially from remote or densely populated areas. There is also the problem of storage and preservation. Organic fertilisers, if not properly stored, can lose their nutrient value, or become contaminated. Establishing and maintaining storage facilities that preserve the quality of these fertilisers can be a challenge. Thirdly there is a problem with the distribution network. Once processed, the fertilisers need to reach the farmers. Building a reliable and cost-effective distribution network, especially in areas with poor road connectivity or other infrastructure challenges, is important.

Many African cities lack effective collection systems, with issues such as inadequate containers for waste, which affects the sanitation process. The transportation of waste is increasingly problematic, as urban expansion requires waste to be moved over longer distances, making the process more expensive and less efficient (Aziale, & Asafo-Adjei, 2013).

The high density and moisture content of waste in many African regions complicate traditional methods of waste collection and disposal. This often leads to faster decomposition and related environmental issues. Developed countries have relied heavily on landfills, but these are becoming unsustainable due to groundwater pollution and space constraints. Conversely, some European nations like Austria, the Netherlands, and Denmark have successfully implemented recycling and waste separation strategies (Aziale & Asafo-Adjei, 2013).

Potential Solutions and Innovations by Reverse Logistics. This concept involves the recycling and reprocessing of materials to reduce environmental impact. It’s seen as a potential way to address logistical challenges through strategic management of the reverse flow of materials, from consumer back to producer. Addressing waste management challenges effectively requires comprehensive community involvement and a rethinking of urban planning to integrate sustainable waste management practices (Aziale, & Asafo-Adjei, 2013).

2.9.2 Market Competition with Traditional Fertilisers

Since the Africa Fertiliser Summit in 2006, which emphasised the critical role of increased fertiliser use in combating land degradation and bolstering food security, there has been a significant shift in perspective due to dramatic price surges (Africa Fertiliser Summit, 2006).

Fertiliser prices have escalated by over 130%, primarily driven by rising petroleum costs. This sharp increase has outpaced the growth in commodity prices, altering the economic viability of fertiliser use that was previously advised. Consequently, profitability models from 2004 were no longer applicable by 2008 hence a cheaper alternative to mineral fertilisers in necessary to achieve food security in SSA (Rogalla et al., 2009).

Farmers have been using synthetic fertilisers for decades and might be hesitant to switch to organic alternatives (Lamine, 2011). Convincing them of the efficacy and benefits of waste-derived fertilisers requires demonstrative efforts and trust-building. Again, the issue of cost may play in the role of usage of organic fertilisers. While waste-derived fertilisers have environmental and long-term soil health benefits, their initial cost might be higher than synthetic counterparts, especially if economies of scale have not been achieved. Competing on price can be a significant barrier. Furthermore, Synthetic fertilisers often come from established brands with significant marketing budgets. Waste-derived fertiliser initiatives might face challenges in creating brand awareness and loyalty, especially in the early stages.

Acknowledging and addressing these challenges is critical for the success of waste-to-fertiliser ventures. While some barriers can be overcome with technological innovations, others require community engagement, policy interventions, and strategic business approaches. Collaboration among stakeholders—ranging from waste managers and researchers to policymakers and farmers—will be essential to navigate and surmount these challenges.

2.10 Future Trends and Research Directions

The evolving landscape of waste-to-fertiliser initiatives is shaped by advancements in technology, growing recognition of sustainable agricultural practices, and global movements towards circular economies. Some areas of promise include the advancement in microbial processes, tailored fertiliser formulations for specific crop needs and soil type, the use of AI and Internet of things to help sort and segregate waste. Leveraging technologies like Artificial Intelligence (AI) and the Internet of Things (IoT) can optimise the waste processing parameters in real-time, ensuring maximum nutrient recovery and efficiency in SSA (Sharma et al., 2020).

2.10.1 Integration with Other Sustainable Agricultural Practices

Sustainable agriculture is characterised by practices that reduce soil disturbance, maintain permanent soil cover, and utilise crop rotations to enhance farm productivity and sustainability. These practices are vital for preserving water and soil quality, maintaining soil organic matter (SOM), recycling and storing nutrients, optimising the use of natural resources, and preventing soil degradation (Srivastava et al., 2020). The soil, alongside air and water, is essential for terrestrial life (Biswas et al., 2019).

The integration of waste-derived fertilisers into conservation agriculture can significantly improve soil organic matter, boost moisture retention, and enhance overall soil health (Ramteke et al., 2023). Furthermore, sustainable agricultural practices such as agroforestry not only allow for improved soil quality and water management but also facilitate carbon sequestration and increase biodiversity (Kaur et al., 2023). Agroforestry, which involves integrating trees within agricultural landscapes, offers extensive environmental, economic, and social benefits, contributing to diversified income streams for farmers.

In addition to these practices, other sustainable approaches include the use of cover crops, which protect the soil from erosion and improve its fertility by fixing nitrogen and adding organic matter (Scavo et al., 2022). Integrating livestock in rotational grazing systems can also enhance soil health and nutrient cycling. Moreover, polyculture and permaculture practices, where multiple crop species are grown in proximity, can lead to more efficient use of space and resources, further diversifying and stabilizing farm income (Brewer & Gaudin, 2020).

Waste-derived fertilisers play a crucial role in supporting these integrated systems by providing essential nutrients that enhance the productivity and resilience of both tree and crop components (Raniro et al., 2022). As farmers adopt agricultural systems that emulate natural ecosystems, these fertilisers become pivotal in sustaining a variety of plant species coexisting in the same space, thereby optimizing land use, and enhancing ecosystem resilience (Sietz et al., 2022).

2.10.2 Potential for Upscaling and Integration into Broader Circular Economy Frameworks

As urban populations grow, so does the interest in urban farming, including vertical agriculture (Gumisiriza et al., 2022). These systems can directly benefit from nearby waste-derived fertilisers, establishing a hyper-local circular system. Moreso, the future might see more collaborations across the agricultural value chain, where food producers, processors, waste managers, and consumers engage in symbiotic relationships, reinforcing the circularity of resources (Nwele et al., 2020). Moreover, As the global emphasis on sustainable development intensifies, policies and economic instruments (e.g., tax incentives, carbon credits) will likely be more favourable for ventures that align with circular economy principles. This will further drive innovation and upscaling in the waste-to-fertiliser domain.

2.11 Conclusion

Organic waste management in SSA presents a unique blend of challenges and opportunities (Rege and Sones, 2022). By understanding the sources, characteristics, and prevailing management practices, stakeholders can devise strategies for resource recovery, converting waste challenges into sustainable solutions. Technologies such as anaerobic digestion, composting, vermicomposting and biochar production demonstrated viable methods for repurposing organic waste into valuable resources, emphasising the importance of tailoring these approaches to the African contexts. This enables communities and industries to not only achieve sustainable waste management but also contribute to the circular economy.

The prospect of using recovered fertilisers is promising for sustainable agriculture, provided their safety and quality are ensured through adherence to stringent treatment processes and guidelines. This ensures that fertilisers enrich the soil and crops without harming human or environmental health. The economic aspects are also crucial for the success and scalability of waste-to-fertiliser projects. By navigating costs, market dynamics, and incentives efficiently, these initiatives can be economically viable and environmentally beneficial. Converting organic waste into fertilisers has significant environmental and sustainability benefits, contributing to waste reduction, climate change mitigation, and biodiversity conservation. These efforts support more resilient and productive agricultural systems, aligning with global sustainability goals.

The future of waste-to-fertiliser initiatives is bright, with emerging innovations and a shift towards sustainable, circular practices offering the potential to transform waste into a valuable agricultural resource. Addressing challenges through technological advancements, community engagement, policy interventions, and strategic business models is essential for success. Collaboration across various stakeholders will be key to overcoming obstacles. Studying the successes and challenges of existing waste-to-fertiliser initiatives in SSA offers valuable lessons for new projects and policymakers. This knowledge can help expand the impact across the continent, harmoniously transforming waste management and agriculture.

Furthermore, robust policy and regulatory frameworks are vital for fostering an environment that supports the growth of these initiatives. Addressing challenges and gaps, and fostering collaborative efforts among all stakeholders, can create a strong regulatory landscape.

Finally, the social and cultural dimensions play a crucial role in the adoption of waste-derived fertilisers. Initiatives must resonate with local beliefs, perceptions, and socio-cultural norms. Adopting a participatory and inclusive approach, which values local insights and engages communities, is critical for navigating these complexities and ensuring the success of waste-to-fertiliser ventures.

3 Assessing the fertilising property of different anaerobic digestates on early growth and development of a dwarf tomato cultivar

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Abstract

This research focuses on comparing the growth performance of micro-tom tomatoes fertilised with digestate obtained from different anaerobic digestion processes using feedstocks from municipal, agricultural, and food waste streams in the UK and Ghana. The study was conducted on low-nutrient acidic sandy podzols, and the aim was to assess the effects of the fertilising materials on plant growth. The fertilising materials used were urea (positive control), Safisana, Cockerham, and Inoculum to Substrate Ratio = 2.0 (ISR = 2.0), applied at a rate of 100 kg N/ha, equivalent to 0.415 g to 2.5 g N/kg soil dry basis. Unamended soils served as the negative control. The addition of the fertilising materials increased total available nitrogen content (NH_4^+-N and NO_3^--N) of the soil with the record of highest being Urea at 10.2 mg/kg followed by ISR = 2.0 at 6.313 mg/kg compared the unamended soil at 1.3 mg/kg and improved growth compared to the unamended treatments. Tomatoes treated with digestate produced dry above-ground biomass of 0.48 g - 0.72 g (55-78%) compared to 0.88g of urea fertiliser. These results highlight the significant growth-promoting effects of digestate, and mineral urea fertilisation compared to the unamended treatments.

3.1 Introduction

The population of Sub-Saharan Africa (SSA) is expected to increase to two billion people by the year 2050 (Smith et al., 2014). This means there is a pressing need to provide enough food to feed SSA. The mass balance of applied nitrogen (N) is a crucial parameter for evaluating the efficiency of fertiliser use in agricultural systems. It helps in understanding the fate of applied nitrogen and is essential for optimising fertiliser application to minimise environmental impacts while ensuring optimal plant growth (Da-Ros et al., 2023). In SSA, soil fertility is notably declining, primarily due to the loss of organic matter and the non-replenishment of key soil nutrients such as Nitrogen (N), Phosphorus (P), and Potassium (K). This nutrient depletion, resulting from overuse of the land, erosion, and inadequate nutrient replacement, leads to an estimated annual loss ranging from 10 to 70 kg N/ha, 2 to 10 kg P/ha, and 8 to 50 kg K/ha across SSA nations. These figures highlight the critical state of soil fertility and its direct impact on food security in the region (Stoorvogel and Smaling, 1998; Raimi et al., 2017; Zingore et al., 2017).

In general, low soil fertility leads to low crop productivity. Given that the majority of SSA's soils are inherently low in nutrient content, few soils supply enough N to sustain satisfactory crop production without fertiliser inputs (Bobo et al., 2017). Hence, N deficiency is more prevalent than any other nutrient deficiency in crops (Bobo et al., 2017). The reliance on mineral fertilisers alone is not a viable long-term solution due to their cost and often limited availability to resource-constrained farmers. Without intervention with a cheap alternative source of nutrient supply like organic fertilisers, it will be difficult to achieve food production sufficiency.

Digestate, a by-product of anaerobic digestion (AD), offers a cost-effective organic fertiliser alternative (Smith et al., 2014). It is rich in nutrients essential for crop production and has been successfully utilised in various developed countries. Its benefits include supplying beneficial micro and macro-nutrients that restore soil fertility and enhance crop productivity, depending on the digestion process's substrates (Barzee et al., 2019; Sapp et al., 2015; Makadi et al., 2012). SSA's diverse sources of substrates for AD, ranging from food to animal and agricultural waste, present an opportunity to produce nutrient-dense digestate for agricultural use.

While digestate has been recognised for its benefits in crop production and is well-documented in various global studies, its utilisation in SSA remains underexplored. The existing literature predominantly focuses on other regions, leading to a notable gap in research concerning digestate's application and efficacy in SSA's unique agricultural contexts. This underlines the need for more targeted studies in SSA to fully understand and leverage digestate's potential in enhancing crop productivity within the region. Digestate contains agronomically significant levels of nitrogen (N), highlighting its potential as a valuable resource for enhancing soil fertility and supporting crop growth (Tallou et al., 2021; Czekała, 2022). This characteristic positions digestate as an important alternative to conventional fertilisers, offering a sustainable means of supplying essential nutrients to crops. According to Lukehurst et al. (2010), digestate contains an estimated amount of 4-60% N, with 3-30 kg/m3 as ammonium N (NH_4^+-N), and 0.7-12 kg/m3 as nitrate N (NO_3^--N). According to Kirchmann and Witter (1992), anaerobic digestion of manure could result in ammonium N concentrations constituting 50-75% of the total N in the digested material. With N being the most limited nutrient in SSA soils (Kiboi et al., 2019), the application of digestate can have a positive impact when applied as fertilisers for food production, especially for the cultivation of tomatoes (Tallou et al., 2021).

Tomato is a very important food ingredient in West Africa as it is the main ingredient for soups and sauces. The plant grows well on sandy loam soils with pH between 5 to 7 (FAO, 2022). Although many authors have studied the effect of different digestate types and the overall effects on different crops, very few have highlighted the effect of digestate on the growth of tomato plants. Tallou et al. (2021) reported that tomatoes treated with biofertilisers with total Nitrogen (TN) of 1.63 g/kg to 13.22 g/kg showed good performance, high fruit quality, and tomato yield compared to control conditions.

Tomatoes require essentially all the macro and micro-nutrients for their establishment but need N in larger quantities at the initial stage of growth. N is a significant component of enzymes, vitamins, chlorophyll, and other cell constituents, all of which are essential for crop growth and development (Kishorekumar et al., 2020). Plants that are deficient in N exhibit stunted growth and gradual leaf yellowing but respond quickly to N inputs (e.g., leaves turn deep green in colour due to the central role of N in chlorophyll synthesis) (Luce, 2011). Thus, the importance of N in crop growth cannot be overemphasized. The recommended fertiliser requirements amount for tomato is 100 to 250 kg/ha N, 65 to 110 kg/ha P, and 160 to 240 kg/ha K (FAO, 2020). On an economical scale, a near-low application rate is likely to be adopted when applying fertiliser to large hectares of land with expensive mineral fertilisers in SSA (AUDA-NEPAD, 2021).

The study of digestate and its application in agriculture has been extensive (Mupambwa, et al., 2019; Dahunsi & Ogunrinola, 2018). However, few studies focus on specific soil types such as Podzols and Acrisols which are characterised by weathered and/or acidic sandy soils. The research focus has been on field trials with recommended application rates not targeted for the SSA African farmer and crops likely to be grown. There is a growing interest in using digestate as a sustainable alternative to chemical fertilisers, with several studies highlighting its nutrient-rich composition, especially in nitrogen, which is essential for plant growth. For instance, Cristina et al. (2020) observed significant increases in tomato biomass and height, up to 37.5% and sixfold respectively, when digestate derived from sewage sludge was applied at a rate of 170 kg N/ha, without any phytotoxic effects. This study, along with others, suggests that digestate can enrich soil with both macro- and micro-nutrients, thereby enhancing plant nutrient uptake and organic matter content.

However, research also reveals variability in the effectiveness of digestate-based fertilisation. Dahunsi & Ogunrinola (2018) reported improved morphological traits and soil microorganisms in tomatoes with higher applications of biofertilisers, although the exact rate of application was not specified. Conversely, Mupambwa et al. (2019) found that hydroponic tomato cultivation with cow-based digestate yielded lower compared to chemical fertilisation, suggesting that not all types of digestate may be suitable as nutrient media. Asp and Bergstrand's study (2024) further emphasizes this variability, noting that while digestate fertilisation contributed to biomass production, it did not match the output achieved with mineral fertilisers. Specifically, treatments with digestate resulted in only 62% and 47% of the total biomass and a similar reduction in the yield of harvestable fruits compared to the mineral-fertiliser reference.

While previous studies have highlighted the beneficial effects of biofertilisers on crop yield and soil health, there remains a need for a more detailed understanding of how different concentrations of nitrogen present in the digestate influence the morphological traits of micro-tom tomatoes and the physiochemical properties of the soil upon the addition of this biofertiliser. This gap in the literature highlights the importance of further empirical investigation into the nuanced effects of biofertiliser application rates. Therefore, this study speculates the following testable hypotheses: (1) Higher application rates of biofertilisers (in SSA African context) will lead to a noticeable improvement in soil physiochemical traits (2) similar application rates to those applied in SSA mineral fertilisers to tomatoes will significantly enhance their growth and morphological traits compared to plants treated with conventional urea fertilisers.

To test this hypothesis, a proof-of-concept experiment was conducted to test multiple digestate sources on the growth of micro-Tom tomato (*Solanum lycopersicum* L.) cultivar with chemical fertiliser. The choice of the micro-Tom cultivar was strategic, given its lower nutrient demands compared to taller tomato varieties. This characteristic allows for a more nuanced assessment of the digestate's efficacy in supporting plant growth under conditions where nutrient requirements are modest. By demonstrating positive impacts on the micro-Tom, we aim to highlight the potential of digestate as an effective fertiliser, even in scenarios where nutrient demands are not as intensive, thereby broadening the scope of digestate's applicability in sustainable agricultural practices. By testing these hypotheses, this research aims to contribute to the optimisation of biofertiliser use in tomato cultivation in SSA, offering insights that could lead to more sustainable agricultural practices.

3.2 Materials and Methods

3.2.1 Experimental design and set-up

The experiment was conducted in a naturally lit greenhouse space located at Lancaster Environment Centre, Lancaster University, UK. The test crop was micro-Tom (dwarf variety of tomato). The temperatures in the glasshouse for tomatoes were controlled to be between 25 ^{o}C maximum during the day and 16 ^{o}C minimum at night. There were Sixteen (16) hours of day light and eight (8) hours of darkness.

Micro-Tom seeds were germinated on moistened filter papers placed on petri dishes for 14 days in at room temperature. Digestate and mineral fertilisers were applied at 100 kg/ha N. To achieve this between 0.02 to 2.51 g of N either in form of digestate or mineral fertiliser was applied to 1000g of dry soil, excluding the unamended soils (negative control). One and half litre (1.5 l) pots with dimensions (11cm height *8cm bottom diameter) were filled with soil digestate mixture and left overnight, and planting was done the following day. A total of 3 seedlings from the 7-day old micro-Tom were planted in each pot. Seedling were planted in a and well-watered conditions to prevent seedling transplanting shock. There were 7 replicates in each treatment in a completely randomised block design. Soils were watered to saturation on day one and after 3 days the target moisture content of 60% of the water holding capacity was achieved. Regular watering was done to maintain the target moisture content (Appendix 2). Daily watering was done by weighing the total mass of the pots and topping up the evaporated water. The digestates treatments were compared with mineral fertilisers as a positive control and unamended soil as a negative control to assess the fertiliser quality on the growth and above ground biomass of tomatoes.

3.2.2 Digestate source and collection

Five treatments were considered for this experiment comprising of three digestate sources, urea fertiliser and unamended soil. The three different digestates samples were namely Cockerham Green, Inoculum to Substrate ratio of 2 (ISR = 2.0) and Safisana. The Cockerham Green and ISR = 2.0 were sourced from Lancaster UK and Safisana sourced from Ghana, West Africa. Digestate from Cockerham Green Energy Ltd. The feedstock is livestock and poultry manure, co-digested with wheat grains, potatoes, and whey. The ISR = 2.0 digestate was generated from simulated food waste as substrate and inoculum from Cockerham Green energy limited through batch digestion experiments (Gandhi et al., 2022). Unlike ISR = 2.0 and Cockerham Green digestate which were in the whole form, the Safisana digestate were sun dried digestate solids generated from a digester fed with organic fraction of municipal solid waste in Ghana. The digestate samples were stored in cold rooms under 4^oC upon arrival.

3.2.3 Digestate characterisation

The samples were analysed for pH, electrical conductivity (EC), total solids (TS), Volatile matter (OM), total N (TN), available N (NH_4-N and NO_3-N) and elemental composition (C and N). The pH and the EC of the samples were measured using a ratio of 1:5 (i.e. one part of soil and five parts of ultrapure milli-Q water). The measurement of the pH and the EC were done with a Mettler Toledo® Seven Compact™ S220 pH/Ion meter and a Jenway® 4510 bench conductivity/total dissolved solids meter, respectively. Briefly 5 g sample mixed with 25ml (1:5) water followed by pH meter reading. Total solids (TS) and volatile solids (VS) determined using standard methods (APHA, 2012). Extractable NH_4^+-N, NO_3^--N were determined for the digestate and urea. NH_4^+-N and NO_3^--N were extracted from soils using a 2M KCl solution and determined using the auto analyser (AA3, SEAL analytical; Method No G-102-93 Rev. (multitest MT7/MT8). Sub-samples of the digestates were sent to NRM Laboratories, UK where the TN of the digestate samples were determined. The digestate characteristics are shown in Table 3.1 Nutrient composition of Digestate and Urea although the full digestate characterisation is provided in Section 3.6. All chemical analyses were performed in triplicates.

Table 3.1 Nutrient composition of Digestate and Urea

Parameter	**Acronym**	**Units (fresh basis)**	**Safisana**	**Cockerham Green**	**ISR = 2.0**	**Urea**
Dry Matter	DM	%	68.9 ± 2	7.8 ± 2	3.61 ± 0.2	-
Ph	pH	-	5.8± 0.2	8.3 ± 0.5	8.6 ± 0.4	8.0 ± 0.1
Electrical Conductivity	EC	mS/m	305 ± 5	749 ± 3	577 ± 4	-
Total N	TN	g/kg	23.5 ± 1.0	6.2 ± 0.2	3.9 ± 0.2	460

Mass of Digestate	MD	g/kg of soil	0.41 ± 0.1	1.58 ± 0.1	2.51 ±0.1	0.02
Total Carbon	TC	g/kg	146 ± 1.2	263 ± 0.68	121 ± 0.67	-
Total Phosphorus	TP	g/kg	14.0 ± 1.0	1.2 ± 0.4	0.7 ± 0.1	-
Total Potassium	TK	g/kg	6.3 ± 0.1	3.9 ± 0.3	6.4 ± 0.1	-

3.2.4 Soil source and collection

Prior to using the experimental soil, some soil samples called *Ferric Acrisol* was obtained from Ghana, West Africa and characterised. *Ferric Acrisol* is a sandy loam derived from weathered tertiary sands and is among the dominantly cultivated soils in the part of the semi-arid tropics in Ghana. Morphologically the soil is well drained, and colour varies from red to brown. The soils have moderate acidity of pH 5.0 – 6.0. Information of *Ferric Acrisol* obtained was used in sourcing the experiment soil. The Experimental soil was then sourced from the England Forestry Commission, Abbots Moss Nursery Delaware in Cheshire, UK and transported to Lancaster. The soils were sieved through a 2mm sieve and stored in cold rooms until use. The soil particle size distribution was determined using laser diffractometer (Coulter Beckman LS13320). Briefly 5-gram soil samples were soaked in 5 -10 ml hydrogen peroxide for 24 hours to remove organic matter. The soil sample is dispersed in a liquid medium to separate individual particles. The dispersed soil sample is introduced into the laser diffractometer instrument. The laser beam passes through the sample, and the scattered light is collected at various angles. The instrument detects and analyse the diffraction patterns to determine the particle size distribution based on the measured diffraction patterns. Measurements were done in triplicates. The particle size distribution was 80 % sand and 20 % silt hence soils were classified as sandy soil. Soil data was provided by the forestry commission. The soils were characterised as Podzols with pH of 6.5. Soil water holding capacity was also determined to be 28 ± 2 % dry weight. The experimental soil samples (Podzols) had similar texture when compared with the *Ferric Acrisol* hence used for the experiment as a synthetic Ghana soil presented in Table 3.2.

Table 3.1 Characteristics of Experimental Soils

Parameter (fresh basis)	Acronym	Units	Ferric Acrisol	Sandy Podzols	P-Value
Volatile solids (Organic matter)	OM	%	4.79 ± 0.1	2.24 ±0.1	1.55×10^{-5}
pH	pH	-	5.8 ± 0.1	6.5 ±0.1	5.54×10^{-5}
Electrical Conductivity	EC	uS/cm^3	25.7±2.1	51.33 ± 1.33	6.68×10^{-5}.
Total Nitrogen	TN	%	0.3 ± 0.1	0.08 ±0.1	0.00934
Total carbon	TC	%	1.2 ± 01	1.3 ±0.1	0.10124

Carbon: Nitrogen ratio	C: N	-	4 ± 0.1	16 ±0.1	3.42×10^{-8}
Total phosphorus	TP	%	0.027± 0.01	0.014 ±0.1	0.90509
Particle size analysis	Clay	%	7.7 ± 0.1	0.6 ±0.1	1.64×10^{-8}
	Silt	%	4.7 ± 0.1	2.5 ±0.1	2.41×10^{-8}
	Sand	%	87.6 ±0.2	97.0 ± 0.3	1.29×10^{-5}

3.2.5 Data collection

Growth (morphological) parameters such as plant height, stem diameter, were measured weekly from week 2 to 6 weeks. Plant height was measured using a tape-measure while the stem diameter was measured using the digital vernier calliper. Number of leaflets and leaf area were determined at the end of the experiment. Number of leaflets were counted when the leaf area was being measured as each leaflet was taken one after the other. Leaf area was measured using a digital area meter (Model 3100, Li-Cor, NE, USA) at the end of the experiment. Above ground biomass was measured by cutting plant stem just above the top of the soil mass in the pots using scissors. The cut above ground biomass were kept in sample paper bags.

3.2.6 Water Application

Plants were well irrigated throughout the experiment. Target water application was set to be 145 ml. Water added daily was what was lost through evapotranspiration. Results of evapotranspiration and cumulated water application are presented in Appendix 7.1.1.4

3.2.7 Post Planting analysis

Plant biomass collected from the pots were weighed for determination of its wet weight (WW), and oven-dried at 55 °C for 120 hours for the determination of samples dry weight (DW) content. The dry samples were then ball milled to pass a 1 mm sieve (Retsch SM-2000, Germany) and C and N were determined using the elemental analyser.

3.2.8 Mass Balance / Change in Stored N

A mass balance approach was used to calculate the fate of nitrogen applied in various fertiliser treatments. The inputs were the mass of nitrogen added through fertilisers, and the outputs were the nitrogen content found in the soil and plant biomass after a growth period. The key components considered in the mass balance were:

$$\text{Change in Stored N} = N_{\text{inputs}} - (N_{\text{outputs in soil}} + N_{\text{outputs in Biomass}}) \quad \text{Eq. (1)}$$

Where:

- N_{Inputs} = Total nitrogen applied as fertiliser to the soil system.
- $N_{\text{Outputs in Soil}}$ = Nitrogen present in the soil, measured as a percentage of the total soil mass (assumed to be 1 kg for calculation purposes).
- $N_{\text{Outputs in Biomass}}$ = Nitrogen present in the plant biomass, determined by the nitrogen concentration in the dry biomass matter.

3.2.8.1 Calculations

The calculations performed for each fertiliser treatment involved the following steps

i. The nitrogen content in the soil was computed by multiplying the percentage of nitrogen in the soil by the soil mass.

ii. The nitrogen content in the biomass was determined by multiplying the percentage of nitrogen in the biomass by the mass of the dry biomass.

iii. The change in stored nitrogen, which represents the unaccounted nitrogen (positive or negative), was derived by subtracting the sum of the nitrogen in the soil and biomass from the total nitrogen inputs.

iv. The resulting values provided insight into the efficiency of nitrogen use and the potential environmental impact due to nitrogen losses.

3.2.9 Statistical Analysis

Analysis of Variance (ANOVA) was used for the analysis to determine the level of significance regarding the effect treatments have on leaf area, plant height, above ground biomass of tomatoes. Each treatment with seven replicates as blocks were analysed. Tukey post-hoc test was used to compare the means at a significant interval of 95% ($p<0.05$) using SPSS 26.

3.3 Results and discussion

3.3.1 Effects of pH and Electrical Conductivity on planted soil.

Overall, the was no significant difference ($p>0.05$) on the pH from day 0 to day 42 (Table 3.3), although there was a general decrease in the pH. Addition of fertilising material slightly increased the soil pH from 6.5 to values ranging from 6.61 to 6.86. Upon addition of fertiliser on the initial day, there was no significant difference ($p>0.05$) between ISR=2.0 and Cockerham Green but different when compared with the Safisana fertiliser. Comparing the positive control to the organic sources of fertiliser there was no significant difference ($p>0.05$) between them but significant different ($p<0.05$) when compared with the negative control on the initial day. On day 42, there was no significant difference (p>0.05) between the Urea fertilisation, Cockerham Green and ISR = 2.0 but significantly lower (p<0.05) when compared with the Safisana and the unamended soil. There was also a general decrease in the EC from day 0 to day 42 (Table 3.3). On day 0, there was no significant difference (p>0.05) between Urea, Cockerham Green and ISR= 2.0 but different when compared with Safisana and the unamended soil. On day 42, there was no significant difference (p>0.05) between the fertilising materials and the unamended soil.

Table 3.2 Effects of fertilising material on pH and Electrical Conductivity (EC). Values with the same letters in column are not significantly different (P<0.05) level as determined using a Tukey post-hoc test)

Fertilising Material	pH Day 0	pH Day 42	EC Day 0	EC Day 42
Safisana	6.74 ± 0.10 bc	6.80 ± 0.04 b	55.9 ±4.59 bc	27.7 ±1.0 a
Cockerham Green	6.85 ± 0.07 a	6.80 ± 0.01 a	64.70 ± 2.15 a	24.8 ± 0.5 b
ISR = 2.0	6.86 ± 0.01a	6.80 ± 0.04 a	65.0 ± 1.77 a	23.9 ± 1.0 b
Urea	6.86 ± 0.66 ac	6.70 ± 0.04 a	60.8± 0.32 ac	23.7 ± 0.8 ab
Unamended Soil	6.61 ± 0.18 b	6.40 ± 0.05 c	51.6 ± 0.32 b	22.7 ± 0.5 ab

The effect of fertiliser on the pH of the soil can vary depending on the type of fertiliser used, soil pH and the reactions that may occur in soil when fertiliser is added. However, their impact on pH can indirectly occur through the uptake of nutrients by plants. As plants take up nutrients, the nutrient absorption processes can influence soil pH (Ferrarezi et al., 2022). Thus, the uptake of some cations like magnesium and calcium if present in the fertilising material can replace hydrogen ions on soil exchange sites, leading to a slight increase in pH. However, if the is ammonium-based (NH_4^+), fertilisers are added to ions release may lead to a decrease in soil pH over time (Wang et al., 2020). This is because ammonium ions can undergo nitrification, a microbial process where they are converted to nitrate ions (NO_3^-) and hydrogen ions (H^+) (Ward, 2008). The release of hydrogen ions increases the soil's acidity as observed from study. Inorganic fertilisers (mineral-based) generally have a more direct impact on soil EC compared to organic fertilisers. Changes in the pH, impacts on some ions (such as magnesium, calcium, and trace elements) availability which in turn affects the concentration of ions and EC. The presence of salts in a solution can influence both pH and EC. Electrical conductivity (EC) can decrease in soil solution primarily when the concentration of dissolved ions or salts decreases. The EC decrease from day 0 to day 42 indicates that nutrients was used up for plant growth (Argo and Fisher, 2009).

3.3.2 Extractible Nitrogen from soil

Upon application of all the fertilising material (wet), plant available N (NH_4^+-N and NO_3-N) content increased significantly higher ($p<0.05$) in soils compared to the unamended soil. Urea fertilisation had the highest available N (10.2 ± 0.4 mg/kg) content on day 0. The increase was significantly higher ($p<0.05$) than that of the digestate as shown in Figure 3.1. Of all the digestates applied, ISR = 2.0 had significantly higher ($p<0.05$) total available N (6.3 ± 0.3 mg/kg) followed by Cockerham Green (6.2 ± 0.6 mg/kg) while Safisana digestate had the least available N content (2.3 ± 0.2 mg/kg). Plant nutrients are categorised as immediately available, rapid release, slow release and unavailable. Several authors have reported that digestate provide a rapid release of N when applied to the soil. This is because AD mineralises the nutrients and hence readily available upon application to soil as shown in Figure 3.1. Post planting analysis (Section 3.3 – Section 3.7) revealed that, the available portions of N were used during the 42 days of planting. Apart from the unamended soil, there was a reduction in quantity for all treatments (Figure 1.1). Available N was highest in Urea treatment followed by Cockerham, whiles Safisana and ISR = 2.0 were the same on day 42. As expected, the Urea amendment has the highest performance compared to the digestate amended treatments. Urea had the highest form of the NH_4^+-N and NO_3^--N available in them. According to Makádi, et al., (2012) the yield parameters are in close correlations with the soil parameters, such that increasing the important nutrient contents in soil contribute to the better development of the plants.

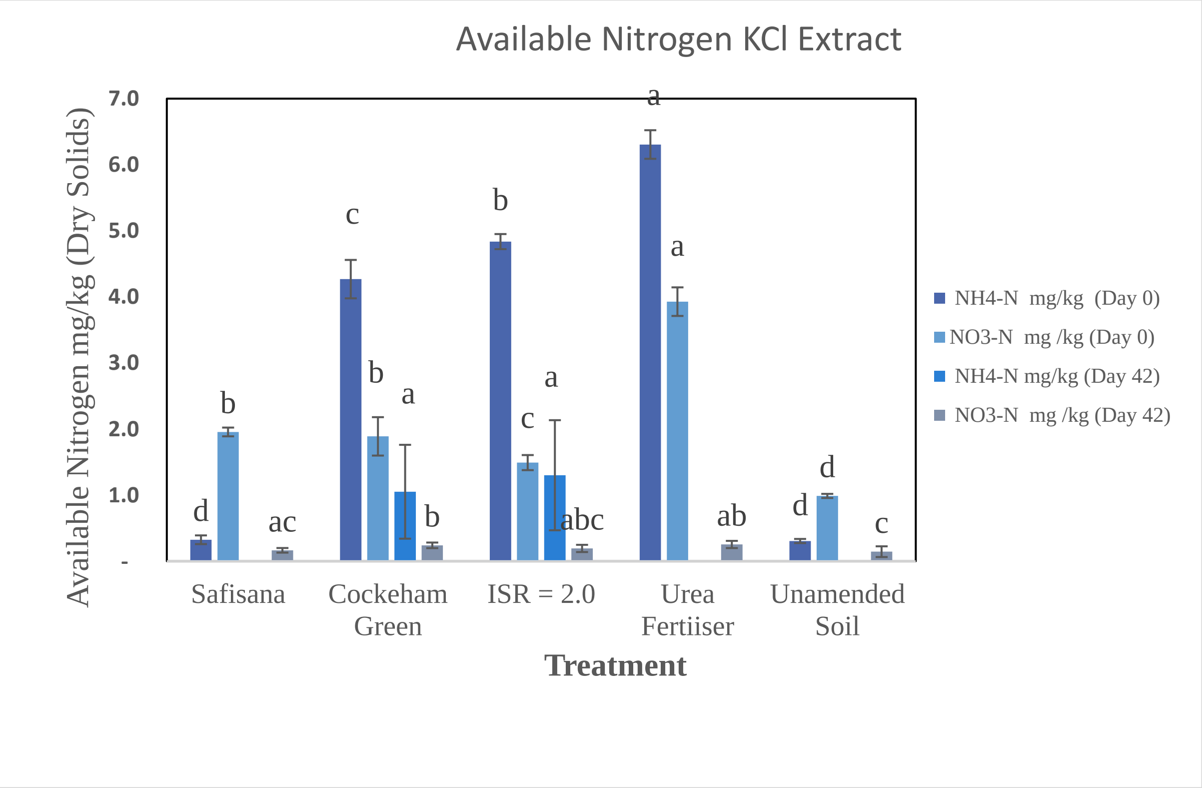


Figure 3.1 Available N (NH_4^+-N and NO_3^--N) of day 0 and Day 42; Same letters (among similar colours) are not significantly different at the "$p<0.05$" level asdetermined using a Tukey post-hoc test. The bars represent the mean ± standard deviation. The letters over the bars are the results from a Tukey Pairwise Comparison. The same-coloured bars that do not share a letter are significantly different at 95% confidence level

3.4 Effect of fertilising material on plant height and stem diameter.

All the fertilising material had effects on the growth and development of tomato compared to the unamended soil (control treatment) as plants exhibited an increase in height, stem diameter, number of leaflets, total leaf area, the wet and dry weight of the above ground biomass. The presence of nutrients (N) supported plant growth during the six-week period as there were an increase in growth and development of tomatoes for all the treatment. During the early days (day 14 to day 21) there were no significant differences ($p>0.05$) in weekly measurements of the stem diameter. However, the differences were observed from the fourth week (day 28 – day 42) as the urea fertiliser treatment and the ISR= 2.0 recorded higher stem diameter values than the rest of the treatments with no significant differences ($p>0.05$) between the two. The Safisana digestate and the unamended soil recorded lowest values (3.5 and 2.8 mm) in stem diameter on day 42. Urea-fertilised plants had significantly greater ($p<0.05$) growth than those in unamended soil. Digestate had valued N present in them mostly stored as NH_4^+ and other essential elements conserved in there such as P, K and Mg and this leads to a positive fertilising effect of for plants (Barbosa et al., 2014) as observed in the plant growth (Figures 3.2 and Figures 3.3).

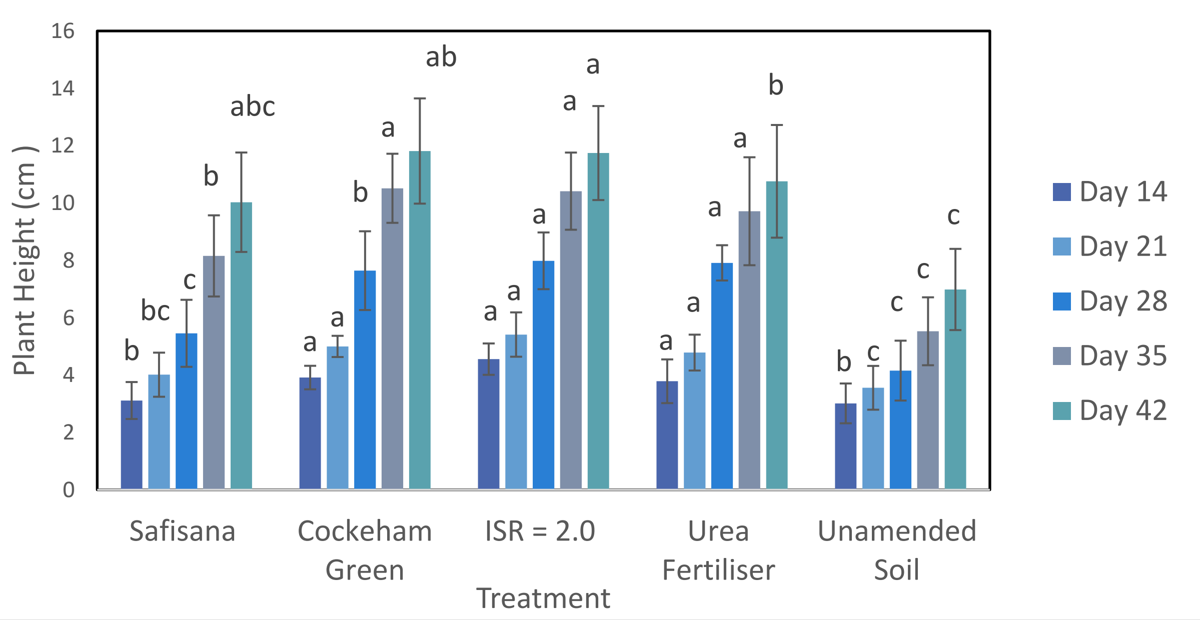


Figure 3.2 Plant height of micro-Tom observed for 42 days. (The bars represent the mean ± standard deviation. The letters over the bars are the results from a Tukey

Pairwise Comparison. The same-coloured bars that do not share a letter are significantly different at 95% confidence level)

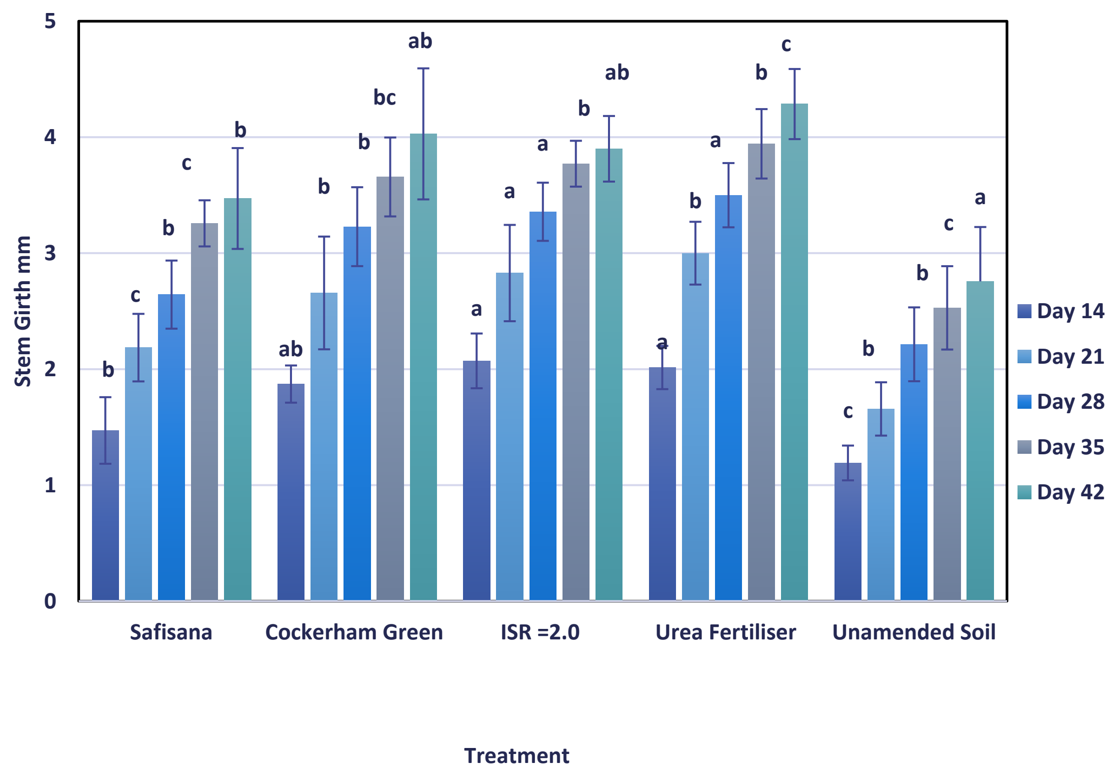


Figure 3.3 Stem diameter of micro-Tom observed for 42 days. (The bars represent the mean ± standard deviation. The letters over the bars are the results from a Tukey Pairwise Comparison. The same-coloured bars that do not share a letter are significantly different at 95% confidence level)

3.4.1 Effect of fertilising material on number of leaflets and total leaf area

The leaf area, increased with an increasing number of leaflets (Figure 3.4). Tomato plants exhibited rapid growth with significantly higher ($p<0.05$) higher number of leaflets and total leaf area being recorded by Urea treatment followed by that of ISR = 2.0. Although there was no significant difference ($p<0.05$) in the number of leaflets among the digestate treatments and the unamended soil, the leaf area recorded from the ISR = 2.0 was significantly higher ($p<0.05$) whiles that of the unamended soil recorded the least. Similar values were recorded for Safisana and Cockerham Green energy whiles the unamended soil (control) recorded the least. Larger leaf area contributed to increase photosynthesis in wheat (Guinta et al., 2008). Increased photosynthesis in leaves leads to increased shoot biomass (Qi et al., 2020) hence the proportional relationship between the number of leaves and leaf area. There was a significant difference ($p<0.05$) between treatments of urea, digestate amendments and the unamended soil in terms of the number of leaves and leaf area. According to Barbadosa, (2014), digestate residue could effectively be used in short term to provide nutrient to crops, although the author did not find a significant difference ($p>0.05$) between in the cumulated dry biomass of *Medigo Sativa L.* subjected to digestate and mineral fertilisers but significantly higher ($p<0.05$) higher yield when compared to plots in the unfertilised controls.

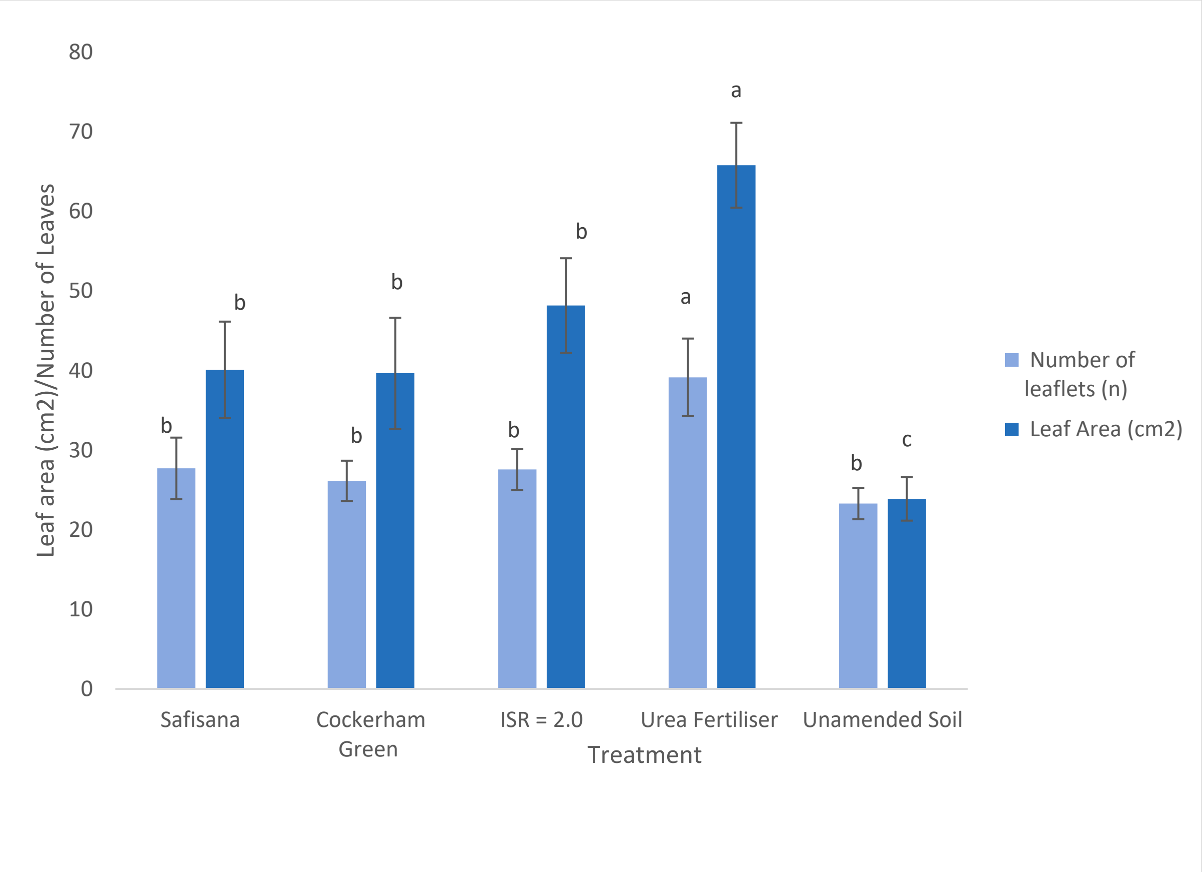


Figure 3.4 Number of leaflets and Leaf Area. (The bars represent the mean ± standard deviation. Same letters (among similar colours) are not significantly different at the P<0.05 level as determined using a Tukey post-hoc test).

3.4.2 Chlorophyll content in emerging leaf

Chlorophyll content serves as a marker for assessing a plant's nutritional status and its response to available nutrients, particularly nitrogen (N), which is critical for photosynthesis and overall plant health (Mupambwa et al., 2019). In this study (Table 3.4), chlorophyll content in emerging leaves was monitored as an indicator of the nitrogen release from fertilising materials. During the initial assessment periods, 14- and 21-days post-planting, chlorophyll content did not differ significantly (p>0.05) among plants treated with different digestates or urea fertiliser. However, these treatments did display significantly higher ($p<0.05$) chlorophyll levels compared to the unamended soil, suggesting enhanced nutrient availability.

Table 3.4: Chlorophyll content (μmol/m^2) of leaf surface (mean ± standard deviation). Values with the same letters in Column are not significantly different (P<0.05) level as determined using a Tukey post-hoc test)

	Days after Planting				
Treatment	14	21	28	35	42
Safisana	315 ± 25 a	401 ± 49a	450 ±3 7 a	376 ±70 a	317 ± 57 ab
Cockerham Green	367 ± 42 a	418 ± 50 a	388 ± 60 ab	326 ± 89 a	246 ± 59 ac
ISR = 2.0	375 ± 53 a	433 ± 60 a	418 ± 40 ab	322 ± 32 a	255 ± 29 ac
Urea	363 ± 41 a	456 ± 49 a	446 ± 69 a	403 ±72 a	364 ± 55 b
Unamended soil	186 ± 77 b	273 ± 83 b	348 ± 50 b	317 ± 68 a	225 ± 53 c

By Day 35, the differences in chlorophyll content between the fertilised treatments and the unamended soil became statistically insignificant ($p>0.05$), which might indicate an equilibrium point in nutrient absorption or a shift in plant growth stages (Ragel et al., 2019). By Day 42, the Safisana and urea treatments notably maintained higher levels of chlorophyll content compared to Cockerham Green, ISR = 2.0, and the unamended soil, with no significant difference ($p>0.05$) between Safisana and urea. This suggests that both treatments provided adequate nitrogen, possibly with a slower release from Safisana, which is beneficial for sustained plant growth. As per Table 3.4, there was a discernible pattern across the weeks. For the first three weeks, there were significant differences ($p<0.05$) in chlorophyll content between the fertilised and unfertilised plants. By the fifth week, urea maintained similar chlorophyll levels to Safisana, but higher than other treatments, indicating a robust nitrogen supply. By the sixth week, despite an overall reduction in chlorophyll content, which could be attributed to plant maturation and the onset of flowering, the urea and Safisana treatments still sustained the highest chlorophyll levels. This pattern highlights that adequate nitrogen supply, through either urea or Safisana digestate, can enhance chlorophyll production, leading to greater biomass due to increased photosynthetic activity. Nitrogen-deficient plants, conversely, exhibit lower chlorophyll content, reduced photosynthetic capacity, and ultimately, lower biomass accumulation. Therefore, maintaining an optimal nitrogen level is crucial for robust plant growth, as evidenced by the higher chlorophyll content in the leaves of plants receiving sufficient nitrogen from fertilising materials.

3.4.3 Effect of Fertilisation on Above-ground Biomass

In general fertilising material treatments affected plant biomass positively compared to unamended soil. The dry weight of aboveground biomass ranged between 0.2 g to 0.9 g. Overall urea fertiliser produced higher values of dry weight above ground biomass at 0.9 g. They were significantly higher ($p<0.05$) higher than biomass produced from the digestate fertilising materials. The results observed can be attributed to higher mineral N (available N) present in urea. Overall, there was a significant difference ($p<0.05$) in the dry above ground biomass between the Urea application and the digestate fertilising material. According to (Makádi et al., 2012) the best application rate of digestate should be based on plant N demand and should be applied when N demand rises based on a high available nutrient content. The form in which N is supplied is of major importance in producing a successful tomato crop. In digestate, N is partly present as ammonium which is directly available for plant uptake and partly as organic N unlike urea where all N are in the plant available form (Bonten et al., 2014). Hence N availability was lower in the digestate than that of mineral fertilisers resulting in the differences observed. The greater above ground biomass accumulation in tomatoes can be related to nutrients availability. According to Qi et al, (2020), the shoot growth is determined by root growth and development which is dependent on acquisition of nutrients present and water availability in the soil. Makadi et al., (2012) states that because of the high available N content, digestate application resulted in significantly higher ($p<0.05$) higher above ground biomass of wheat, sweet corn and silage maize when compared to farmyard manure and undigested slurry in the yield of winter and unamended soils. The author attributed the higher aboveground biomass produced from digestate application to the fact that digestate has soluble macro and micronutrients present in them although the application was splitted into two.

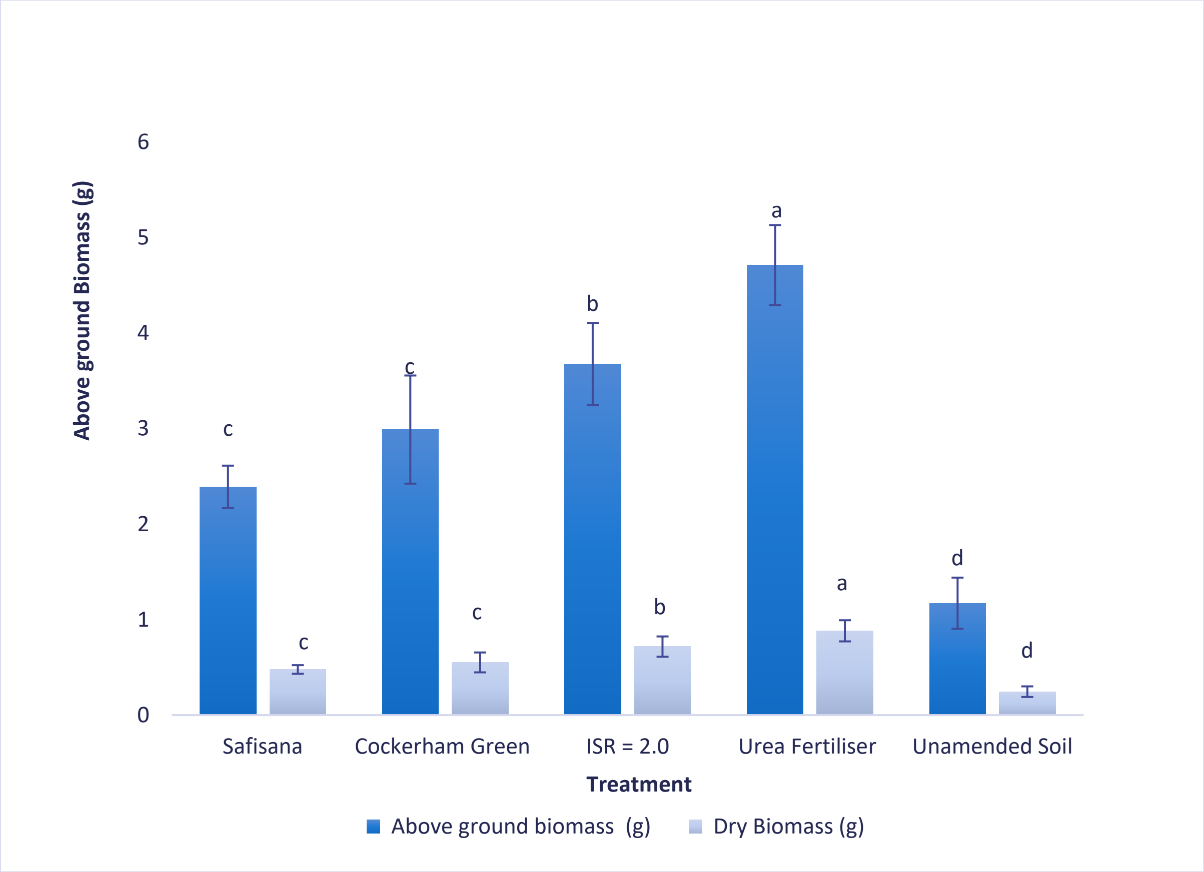


Figure 3.5 Fresh and dry above ground biomass of different treatments. Bars represent means ± SD (n= 7). Same letters (among similar colours) are not significantly different at the P<0.05 level as determined using a Tukey post-hoc test.

3.4.4 Effects of Fertilisation on the Carbon (C) and Nitrogen (N) in Plant Biomass

Averagely, Urea treated samples had significantly higher ($p<0.05$) mass of as TN (20 ± 3 g/kg) and TC (399 g/kg) precent in its total dry above ground biomass value when compared with ISR =2.0, Cockerham Green and the unamended soil but not significantly different ($p>0.05$) when compared with Safisana treated dry above-ground biomass. There was no significant difference ($p>0.05$) between the fertilising materials but significantly different ($p<0.05$) when compared to the unamended soil. This can be explained as that nutrients were conserved in plants because of the slow growth such that plants did not utilize the nutrients for the growth of plants as seen in ISR = 2.0 and Cockerham Green digestate.

Table 3.5 Elemental C and N of above-ground Biomass (mean ± standard deviation)

Treatment	Above-ground Biomass (g)	N g/kg	C g/kg
Safisana	0.5±0.1 c	14 ±3 ab	396 ±3 a
Cockerham Green	0.6±0.1 bc	13 ±1 bc	396 ±4 a
ISR = 2.0	0.7 ±0.1 b	12 ±1 c	395 ± 5 a
Urea	0.9 ±0.1 a	20 ±3 a	399 ±2 a
Unamended Soil	0.2 ±0.0 d	10 ± 1 d	388 ±5 b

There exists a relationship between N nutrient available in fertilising material and the accumulation of nitrogen and carbon in plant biomass. Adequate nitrogen availability can lead to increased plant biomass production (Chen et al., 2018). Limited N nutrient availability can constrain the rate of plant growth reducing plant biomass production. Tomato plants receiving sufficient nitrogen from fertilising material showed higher biomass due to sufficient due to increased photosynthesis leading to enhanced growth processes (Evans, 2013; Kirschbaum, 2011).

Table 3.6 Change in Stored N/ Nitrogen Mass Balance

Fertiliser	**N – inputs**	**N - outputs** **% N in Biomass**			**Change in Stored N /**
		% N in soil	**% N in above ground Biomass**	**% N in unplanted soil**	**Uncounted for +ve or -ve**
Safisana	0.41	0.25	1.45	0.3	0.399851
Cockeram Green	1.58	0.29	1.05	0.32	1.571325
S: I = 0.5	2.51	0.23	1.19	0.32	2.499132
Urea	0.02	0.24	2.05	0.33	-0.00044
Unamended Soil	-	0.3	1.3	0.33	-0.00625

Positive change in stored N indicated that a portion of the applied nitrogen was unaccounted for within the soil and biomass measurements. This suggested potential losses to the environment or errors in the nitrogen input measurements. Negative values indicated that the accounted-for nitrogen in the soil and biomass exceeded the applied inputs, suggesting potential additional nitrogen sources, such as mineralisation of soil organic matter, atmospheric deposition, or fixation, which were not included in the inputs.

In general, the mass balance analysis is critical in assessing the sustainability of fertiliser use. Positive discrepancies in the nitrogen balance could imply nitrogen losses through leaching, denitrification, or volatilisation, potentially contributing to environmental pollution, such as eutrophication of water bodies and greenhouse gas emissions. Conversely, negative discrepancies may reveal soil nitrogen mining, where the soil's nitrogen reserve is being depleted, which could impair long-term soil fertility. These findings highlight the importance of precise nitrogen management practices, including the timing of fertiliser applications, the use of controlled-release fertilisers, and the integration of biological nitrogen fixation strategies to improve nitrogen use efficiency and minimise environmental risks.

3.5 Conclusion

Despite the popularity of anaerobic digestate use in agriculture in many developed countries, application of digestate is yet to accepted and used as a complimentary or even a substitute fertiliser for agriculture in SSA. The study was to test the comparability of the early growth of micro-Tom tomato cultivar between different digestate sources and chemical urea fertiliser of equal amounts of Total N application of 100kg N/ha in laboratory pots experiment.

Results showed that digestate had significantly higher ($p<0.05$) higher values on morphology and dry plant aboveground biomass than the unamended soils. Again, results showed that even though digestate was applied on the same TN application rate as chemical urea fertilisers, the former performed better than the digestate and the unamended soil. Total available N values for digestate ranged between 2.3 to 6.3 mg/kg compared to 10.2 mg/kg of urea. This means that the TN in urea was present in plant available form which makes it easier for plant to absorb and utilise it quickly than the digestate which has its TN content partly in plant available form. However, digestate performed better than the unamended soils. This was seen in plant height and stem diameter, number of leaflets counted, chlorophyll content and the above ground biomass. It can be concluded that digestate can support the early growth and development of micro-Tom tomatoes plants.

3.6 Supplementary Information for Chapter 3

3.6.1 Full Digestate Characterisation of the different digestates

3.6.1.1 Digestate Name ISR = 2.0 and Cockerham Green

	In the dry matter		
Determinant	ISR = 2.0	Cockerham Green	
Bulk Density g/l	1	1	
pH	8.6	8.3	
Oven Dry Solids	8.3	3.61	
Electrical Conductivity us/cm	5773	7936	
Electrical Conductivity ms/m	577	794	
Total N mg/kg	3900	6200	
Total Carbon mg/kg	12160	26340	
Carbon: N Ratio	NA	NA	
Total Phosphorus (P) mg/kg	731	1233	
Total Potassium (K) mg/kg	3970	6345	
Total Magnesium (Mg) mg/kg	267	500	
Total Copper (Cu) mg/kg	4.32		

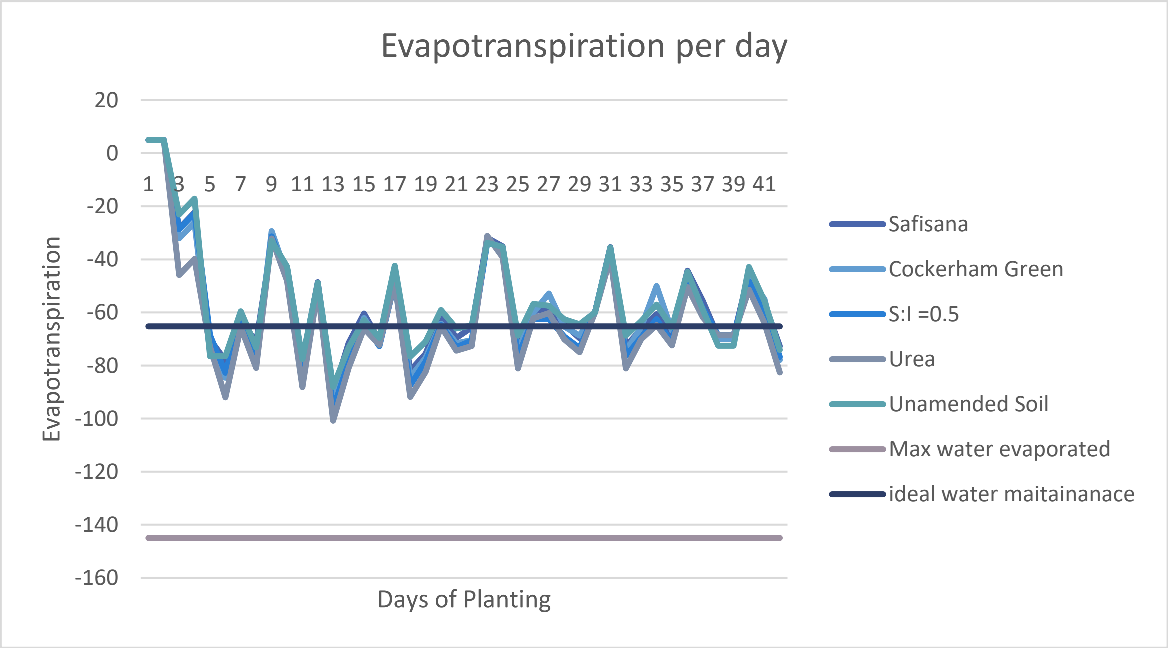
Total Sulphur (S) mg/kg	272		
Total Calcium (Ca) mg/kg	992	-	
Total Iron (Fe) mg/kg	215	-	mg/l
Total Manganese (Mn) mg/kg	21.4	-	mg/l
Total Sodium (Na) mg/kg	1080	-	mg/l
Total Boron (B) mg/kg	1.8	-	mg/l
Total Zinc (Zn) mg/kg	19.7	-	mg/l
Total Lead (Pb) mg/kg	<0.5	-	mg/l
Total Cadmium (Cd) mg/kg	0.02	-	mg/l
Total Magnesium (Mg) mg/kg	-	500	mg/l
Total Mercury (Hg) mg/kg	-	<0.05	mg/l
Total Nickel (Ni) mg/kg	-	0.62	mg/l
Total Chromium (Cr) mg/kg	-	1.11	mg/l
Nitrate N mg/kg	-	<10	mg/l
Ammonium N mg/kg	-	2527	mg/l
Total Molybdenum (Mo) mg/kg	-	0.38	mg/l

3.6.1.2 Characteristics of Safisana Digestate

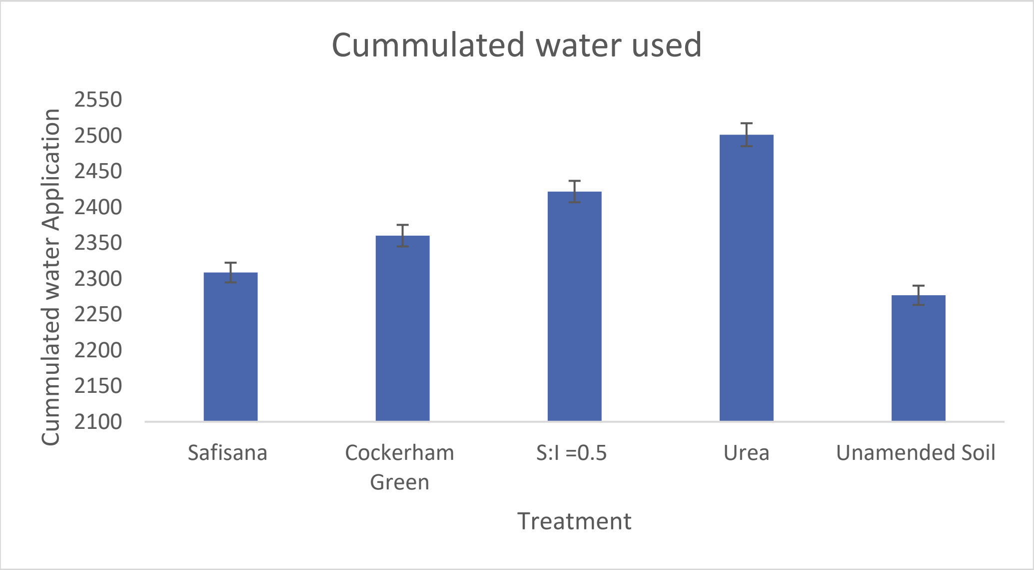
	In the dry matter		As received (Fresh)	
Determinant	Value	Units	Value	Units
Bulk Density			366	g/l
Oven Dry Matter			74.0	%
Moisture			26.0	%
Ph			5.8	
Electrical Conductivity			3054	uS/cm
Electrical Conductivity			305	mS/m
Water Soluble Phosphorus (P)1:5	2452	mg/kg	664	mg/l
Water Soluble Potassium (K)1:5	5388	mg/kg	1460	mg/l
Water Soluble Calcium (Ca)1:5	1867	mg/kg	506	mg/l
Water Soluble Magnesium (Mg)1:5	2613		708	
Water Soluble Sulphate 1:5	2182	mg/kg	591	mg/l
Water Soluble Sodium (Na)1:5	4762	mg/kg	1290	mg/l
Water Soluble Boron (B)1:5	3.4	mg/kg	<1	mg/l
Water Soluble Copper1:5	<1	mg/kg	<1	mg/l

Water Soluble Iron (Fe)1:5	3.8	mg/kg	1.0	mg/l
Water Soluble Manganese (Mn)1:5	3.8	mg/kg	1.0	mg/l
Water Soluble Molybdenum (Mo)1:5	<1	mg/kg	<1	mg/l
Water Soluble Zinc (Zn)1:5	2.6	mg/kg	<1	mg/l
Total N	23590	mg/kg	6390	mg/l
Total Carbon	196800		53309	

3.6.1.3 Water Application Data



3.6.1.4 Cumulative water use



3.6.4.2 Plants were well irrigated throughout the experiment. Target water application was set to be 145 ml. Water added daily was what was lost through evapotranspiration. No significant differences ($p>0.05$) in the water lost through evapotranspiration although urea seemed higher in water loss indicating a higher water usage. The unamended soil recorded lower water loss indicating a low water usage and lower evapotranspiration.

4 Effects of Digestate additions on the cycling of Nitrogen and Phosphorus in soils

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Abstract

This study investigates the impact of digestate application on the cycling of carbon, nitrogen, and phosphorus in two acidic soil types, Ferric Acrisol and sandy Podzols, under controlled conditions. Digestate, a by-product of the anaerobic digestion process, is evaluated for its potential to enhance soil nutrient levels and microbial biomass compared to unamended soil and soil treated with mineral fertilisers. Utilising a soil incubation experiment, the research assesses changes in soil properties including pH, electrical conductivity, available nitrogen (in the forms of NH_4^+-N and NO_3^--N), extractable phosphorus, and microbial biomass carbon, nitrogen, and phosphorus over a 90-day period at varying digestate application rates (22.5, 45, and 90 kg N/ha). These application rates were selected to reflect common fertiliser practices in Sub-Saharan Africa (SSA), aiming to assess the adaptability of such practices to different soil types using organic amendments.

Initial soil and digestate characterisation provided a foundation for understanding the baseline conditions and the nutrient content introduced into the soils. Different rates of digestate application were explored, alongside control treatments of unamended soil and mineral fertiliser, to determine the effects on soil nutrient dynamics and microbial activity. The study reveals significant alterations in soil properties with digestate application, indicating its efficacy as a soil amendment. However, the responses varied between soil types and were influenced by the rate of application, highlighting the importance of tailored soil management practices.

The findings underscore the complex interactions between soil type, fertilisation practices, and the resulting nutrient dynamics. Fertilisation significantly influenced soil electrical conductivity (EC) and the cycling of nitrogen (N) and phosphorus (P). The study contributes to the understanding of digestate's role in sustainable agricultural practices, offering insights into its benefits for improving soil health and nutrient management.

4.1 Introduction

The degradation of vital nutrients, such as nitrogen (N), phosphorus (P), and organic matter, leading to carbon (C) loss in the soils of SSA, necessitates the implementation of effective and sustainable strategies for nutrient replenishment (Jayne & Rashid, 2013). This loss of nutrients is primarily due to factors such as intensive farming practices, soil erosion, and extreme climate events (Hossain et al., 2020). Using a balanced mix of fertilisers, including N and P, is essential for initiating and maintaining nutrient cycles in agricultural systems (Ishfaq et al 2023; Penuelas et al 2023). Moreover, fertiliser application supports soil microbial life and overall soil health, thereby enhancing agricultural productivity and the impact of fertilisers largely depends on the type used (Lazcano, et al 2013). Organic fertilisers are generally recognised for their contribution to the improvement of soil structure, enhancement of water retention capacity, and improvement of microbial life, in contrast to inorganic fertilisers, which are characterised by their higher concentration and ability to provide immediate nutrient availability (Liang et al., 2021; Montgomery & Bikle, 2021). The choice between organic and mineral fertilisers depends on various factors, including the specific nutrient requirements of the soil and crops, cost considerations, and environmental impact (Syed et al 2021). While mineral fertilisers predominantly address the direct nutrient demands of crops, their organic counterparts not only replenish depleted nutrients but also significantly impact microbial dynamics, thereby facilitating the progression of natural nutrient cycles (Noulas and Torabian, 2023; Liang et al., 2021). Among the organic products that can contribute to soil and crop nutrient supplementation is digestate, a by-product of the anaerobic digestion process.

Anaerobic digestion (AD) is a process where waste materials are broken down by microbes to produce biogas and digestate (Ghandhi et al., 2022). Digestate consists of digested organic material, bacteria, and a range of nutrients in both organic and inorganic forms (Midden et al., 2023). Applying digestate to soil has been shown to increase the availability of essential nutrients like N, P, and C, and beneficial microbial presence (Alburquerque et al., 2012). Digestate is characterised by its elevated levels of NH_4^+-N, which contribute to both its microbial stability and enhanced hygiene, thereby making it an effective organic fertiliser or soil amendment when properly handled (Holm-Nielsen et al., 2009; Alburquerque et al., 2012b; Möller & Müller, 2012; Nkoa, 2014). In soil, the organic components of digestate undergo further breakdown by microorganisms through mineralisation, releasing nutrients in a form more accessible to plants (Lazcano et al 2013).

The use of digestate as a soil amendment offers significant advantages over untreated waste, with its effectiveness depending on factors such as organic matter content, nutrient composition, moisture content, pH, and the soil's biotic and abiotic conditions (Sharma et al., 2023).

It is important to consider the specific dynamics associated with using digestate as a soil amendment, considering the unique properties of the digestate itself and the prevailing conditions of the soil. By understanding and managing these factors, the potential benefits of digestate as an effective soil amendment can be harnessed to enhance nutrient availability and promote sustainable agricultural practices.

Nitrogen mineralisation is the transformation of organic nitrogen compounds into inorganic forms, a process primarily facilitated by the enzymes of saprophytic bacteria and fungi, also referred to as ammonification. This ammonification efficiency depends on the quantity of organic matter available for mineralisation in the soil, as well as environmental factors such as soil temperature and moisture (Curtin et al., 2012; Dessureault-Rompré et al., 2015; Goh, 1983; Sakadevan et al., 1993). These factors significantly impact the contribution of mineralised nitrogen to crop nitrogen supply. Assessing nitrogen mineralisation rates in field conditions is challenging due to the dynamic nature of N in the soil. Therefore, short-term laboratory bioassays, usually conducted over about 20 weeks, similar duration to cropping cycle of some crops under controlled conditions, are recommended for estimating soil nitrogen mineralisation rates and understanding mineralised nitrogen availability for crops (Stanford & Smith, 1972).

The current study also touches on phosphorus (P), another vital macronutrient for plants. The natural P supply in most soils is limited, and its availability is typically low (El-Attar et al., 2022). There is interest in enhancing P solubility, influenced by soil pH, through the application of organic fertilisers like digestate (Pang et al., 2024). At a low pH, P tends to bind with Fe and Al, forming compounds that plants cannot easily uptake. Conversely, at high pH P binds with Ca, again becoming less available to plants.

Digestate application can play a role in adjusting the soil pH towards this optimal range, thereby enhancing P availability to plants. Microorganisms also play a key role in phosphate release (Butterly et al., 2009). While digestate can be beneficial for soil fertility, understanding its long-term effects, including potential impacts on soil pH, nutrient retention, and microbial communities, is important for sustainable management practices.

The primary focus of this study is to examine the dynamics of nitrogen (N), phosphorus (P), and microbial biomass in two types of acidic soils amended with digestate under controlled conditions. The study involved a soil incubation experiment with different rates of digestate application of N (22.5 – 90 kg N/ ha) and P (15 kg P/ha – 45 kg P /ha) in addition to control treatments of unamended soil and mineral fertiliser (Urea + Phosphorus). Over a 90-day period, the soil samples were regularly collected to assess changes in soil P and nutrient dynamics. The goal was to understand the effects of varying rates of digestate application and to compare its efficacy as a soil amendment against that of unamended soil and soil treated with mineral fertiliser.

4.2 Materials and Methods

4.2.1 Soil source and sampling

The experiment utilised two types of soils, namely *Ferric Acrisol* and *sandy Podzols* (Table 4.1). The *Ferric Acrisol* soil was obtained from a cultivated field in Ghana and characterised accordingly. The soil samples were topsoil, collected from the 0 to 20 cm layer of the field for analysis. The information acquired from the *Ferric Acrisol* soils was then utilised to source the *sandy Podzols*. The sandy Podzols were obtained from the England Forestry Commission, specifically from Abbots Moss Nursery in Delamere, Cheshire, UK. Subsequently, the soils were transported to Lancaster for further experimentation. Both soil types were classified as having a sandy texture. Before use, the soils were air-dried, sieved through a 2 mm sieve to remove any coarse particles, and stored at a temperature of 4°C until required for the incubation experiment.

4.2.2 Soil Initial characterisation

Soils used for the experiment was initially determined for moisture, water holding capacity (WHC), particles size fractions, organic matter, pH, electrical conductivity (EC), cation-exchange capacity (CEC), total Nitrogen (TN), mineral nitrogen (NH_4^+-N and NO_3^--N), total phosphorus (TP) and Inorganic P (IP), Total Carbon (TC). In the first experimental set-up, Ferric Acisols was used in the incubation experiment to explore the interactions of Safisana, NP and Unamended soil. The second set-up expanded the investigation to include both *Ferric Acrisol* and sandy Podzols, aiming to assess the effects of Cockerham Green, Safisana, NP and Unamended soil. The soils were sieved through a 2 mm sieve and stored in cold rooms (4°C) until use. The soil particle size was determined using laser diffractometer (Coulter Beckman LS13320). Briefly five (5) gram soil samples were soaked in 5-10 ml hydrogen peroxide for 24 hours. Using a spatula, about 1 g was fed into the sonicator of the laser diffractometer (Coulter Beckman LS13320) and the relative sizes of the soil particles were determined. Measurements were done in triplicates. The particle size distribution was 80 % sand

and 20 % silt hence soils were classified as sandy soil. Soil water holding capacity was also determined to be 19% dry weight. The *sandy Podzols* had similar texture when compared with the *Ferric Acrisol* hence used for the experiment as a synthetic Ghana soil presented in Table 4.1. Some of the soil analysis data was provided by the forestry commission England and Wales.

Water holding capacity (WHC) was estimated gravimetrically. To estimate the soil moisture at 100% WHC, plastic tubes were filled with soil, saturated with distilled water, and allowed to drain for 12 hours. Soil samples (5 g, fresh weight) were placed into a Petri dish and oven-dried (105 ◦C) for at least 24 hours. After this time, petri dishes with dried soil samples were weighed and total solids were determined. The organic matter (OM) content was determined from the weight loss following ignition in a muffle furnace (Carbolite, CWF 1000) at 550 ◦C for 5 h. Soil pH and EC was determined in aqueous solution using a 1:5 sample/ water ratio. Total C and N contents were analysed in dried samples, using a CN analyser (TruSpec CHN; LECO, Michigan, U.S.A.). Extractable Ammonium - Nitrogen (NH_4^+-N), Nitrate - Nitrogen (NO_3^--N) were determined. NO_3^--N and NH_4^+-N were extracted from soils using a 2M KCl solution and determined in the auto analyser (AA3, SEAL analytical). The extractable NH_4^+-N and NO_3^--N were estimated followed by the flow injection analysis with autoanalyser (AA3, SEAL analytical) by using the colorimetry based on the salicylate, hydrazine, and molybdate reactions, respectively. Microbial biomass (MB) Carbon (C), N and P ware measured in triplicates by the fumigation-incubation method, according to Jenkinson and Powlson (1973) and Brookes et al., (1982). Briefly, six aliquots of fresh soil samples (10 g each) were placed into glass vials, three aliquots being fumigated with Chloroform ($CHCl_3$) at room temperature in fume hoods, while three aliquots were kept untreated at 2 °C for 24 h. Samples were then extracted using K_2SO_4 for MBC and MBC and $NaHCO_3$ for MBP.

Table 4.1 Soil characteristics of Sandy Podzols and Ferric Acrisol

Parameter (fresh basis)	Acronym	Units	Ferric Acrisol	Sandy Podzols	P-Value
Volatile solids (Organic matter)	OM	%	4.79 ± 0.1	2.24 ±0.1	1.55×10^{-5}
pH	pH	-	5.8 ± 0.1	6.5 ±0.1	5.54×10^{-5}
Electrical Conductivity	EC	uS/cm^3	25.7±2.1	51.33 ± 1.33	6.68×10^{-5}.
Total Nitrogen	TN	%	0.3 ± 0.1	0.08 ±0.1	0.00934
Total carbon	TC	%	1.2 ± 01	1.3 ±0.1	0.10124
Carbon: Nitrogen ratio	C: N	-	4 ± 0.1	16 ±0.1	3.42×10^{-8}
Total phosphorus	TP	%	0.027± 0.01	0.014 ±0.1	0.90509

Particle size analysis	Clay	%	7.7 ± 0.1	0.6 ±0.1	1.64×10^{-8}
	Silt	%	4.7 ± 0.1	2.5 ±0.1	2.41×10^{-8}
	Sand	%	87.6 ±0.2	97.0 ± 0.3	1.29×10^{-5}

4.2.3 Digestate source and sampling

Two digestate sources from the UK and Ghana were used for the experiment. Whole, unpasteurised, and unsieved anaerobic digestate were collected from Cockerham Green Energy Ltd., UK. The digestate is fermented in a mesophilic, single-stage digester with a retention time of 50 days. The feedstock consists of livestock and poultry manure, co-digested with food waste, including wheat, potatoes, tea bags, and whey. Whole digestate was sampled directly from the anaerobic digester; no sieving was done. The Safisana digestate, sourced from Ghana, West Africa, was sun-dried digestate made from municipal waste in Ghana. Digestate samples sourced were stored in cold rooms at a temperature below 4°C upon arrival.

4.2.4 Digestate characterisation

The digestate used in the study was comprehensively characterised to determine various properties and nutrient contents. The pH and EC measurements were conducted using a ratio of 1:5, with one part of digestate mixed with five parts of ultrapure milli-Q water. The pH was measured using a Mettler Toledo® Seven Compact™ S220 pH/Ion meter calibrated with pH4, pH7, and pH10, while the EC was measured using a Jenway® 4510 bench conductivity/total dissolved solids meter. Briefly, 5 g of the digestate sample was mixed with 25 ml of water (1:5 ratio), and the pH was recorded using a pH meter. Total solids (TS) and volatile solids (VS) in the digestate were determined following standard methods outlined in APHA (2012). To determine the levels of extractable ammonium-nitrogen (NH_4^+-N) and nitrate-nitrogen (NO_3^--N), sub-samples of the digestate and urea were extracted using a 1M KCl solution. The NH_4^+-N and NO_3^--N contents were then measured using an auto analyser (AA3, SEAL analytical). The estimation of NH_4^+-N and NO_3^--N was performed using a flow injection analysis with the autoanalyzer (AA3, SEAL analytical), employing colorimetry based on the salicylate, hydrazine, and molybdate reactions, respectively. To assess the total nitrogen (TN) content of the digestate samples, sub-samples were sent to NRM Laboratories in the UK. The TN analysis was performed by NRM Laboratories using established methodologies. In addition, elemental C and N in the digestate were determined using an elemental analyser. All chemical analyses were conducted in triplicate to ensure accuracy and reproducibility of the results. Table 4.2 presents digestate characterisation results, providing valuable insights into the nutrient composition and other properties of the digestate.

4.2.5 Mineral Fertiliser (Urea Phosphate (N & P)) source and Usage

Urea was used as N source while triple superphosphate was used as a P source. The content of N was determined using methods already mentioned whiles P was determined using methods already mentioned whiles P was measure using microwave digestible extracted HNO_3. Samples were read using a mass spectrometer.

Table 4.2 Nutrient Composition of fertilising material

Parameter	**Acronym**	**Units (Fresh basis)**	**Safisana Digestate**	**Cockerham Green**	**Urea**	**Super Phosphate**
Dry Matter	DM	%	68.9 ± 0.1	7.8 ± 0.2	-	
pH	pH	-	5.8 ± 0.2	8.3 ± 0.0	-	
Electrical Conductivity	EC	mS/m	305 ±1.0	749 ± 1.0	-	
Total Nitrogen	TN	g/kg	17.5 ± 0.0	7.1 ± 0.0	460 ± 0.0	
Total Carbon	TC	g/kg	146 ± 1.0	263 ±1.0	-	
Total Phosphorus	TP	g/kg	14.0 ± 1.0	1.2 ± 0.3	-	
Total Potassium	TK	g/kg	6.3 ± 0.1	3.9 ± 0.1	-	
Mass Treatment applied for	22.5 Kg N/ha	g/kg of Soil	0.1 ± 0.01	1.58 ± 0.02	0.005 ± 0.0	0.4375 ± 0.1
	45 Kg N/ha	g/kg of Soil	0.21 ± 0.01	1.58 ± 0.02	0.01 ± 0.0	0.875 ± 0.1

	90 Kg N/ha	g/kg of Soil	0.41 ± 0.01	1.58 ± 0.02	0.02 ± 0.0	1.75 ± 0.2

4.2.6 Experimental Design and set-up

A soil incubation experiment investigated the impact of digestate application on soil samples. The experiment involved placing 120 g of soil into 250 ml sample bottles, which were then placed in an incubator at a controlled temperature of 25°C ± 2°C. The experiment considered different application rates of 0, 22.5, 45, and 90 kg N/ha and 15 30 and 45 kg P ha for the NP (Urea and Phosphate) fertilisation. There were two control treatments namely unamended soil (as a control) and mineral fertiliser (as a positive control) containing NP. Each treatment was replicated three times to ensure statistical robustness. The soil samples were incubated for a total duration of 90 days, representing a 12-week period. Destructive sampling was performed at regular intervals throughout the experiment, specifically on days 0, 1, 3, 7, 14, 28, 56, and 90. This sampling strategy allowed changes in soil properties and nutrient dynamics to be assessed over time.

4.2.7 Experimental Procedure and data analysis

The soil incubation experiment was conducted from July 1, 2021, to August 7, 2021, using digestate and mineral fertiliser amendments. The soil samples were placed in 150 ml sample bottles, while a separate portion of soil was placed in Kilner jars for gas sampling. The amendments were applied randomly in triplicate to the soil samples inside an incubator set at a temperature of 25°C. The N application rates followed the recommendations of the Ministry of Food and Agriculture of Ghana (MoFA, 2019), with four levels: 0, 22.5, 45, and 90 kg N/ha/year. The digestate fractions were thoroughly mixed with the soil and then subdivided into the sample bottles for destructive sampling. The moisture content of the soil was adjusted to 60% of the water-holding capacity (WHC) using distilled water. Control soils were left unamended and only received distilled water to maintain the desired moisture level. On the sampling day, 120 g of soil was placed in each sample bottle, and the soil was subsequently sampled on days 0, 1, 3, 7, 14, 28, 56, and 90. For the Kilner jars, the same amount of 120 g of soil was used, but sampling was not conducted. Instead, moisture was added to compensate for any moisture loss. On the sampling days, additional soil samples were collected to determine moisture, pH, electrical conductivity (EC), NH_4^+-N, and NO_3^--N. Microbial biomass carbon (MBC) and microbial biomass phosphorus (MBP) analyses were performed by adding 10 grams of soil to a glass beaker, which was then placed in the fume chamber for 16 - 20 hours. Extraction using K_2SO_4 for MBC and $NaHCO_3$ for MBP was conducted according to the methods described by Riley (1962) and Olsen et al. (1954) for MBC/MBN and MBP, respectively. The concentration of CO_2 was measured using a gas chromatograph (GC). In addition to the respirometry samples, a parallel set of destructive samples was prepared using amber bottles to monitor changes in soil properties over time. These destructive samples were analysed on the same sampling days as the respirometry samples (0, 1, 3, 7, 14, 28, 56, and 90). The moisture content of the destructive samples was checked daily by weighing the amber bottles without lids and adding milliQ water as needed to maintain 60% WHC. The destructive samples were stored in a dark controlled room, alongside the respirometry samples. Destructive soil samples were subjected to analysis to determine microbial biomass C, N, and P. The chloroform fumigation method, as described by Brookes et al. (1985) and Vance et al. (1987), was employed for the extraction. Duplicate fresh soil samples were extracted with and without chloroform fumigation using a 1:5 w/v ratio of soil to 0.5 M K_2SO_4 solution (pH ~ 7). The extracts were filtered using Whatman No. 42 filter paper. The total carbon (TC) content of the extracts was determined using a TOC-L/TN Series Analyser based on a combustion-reduction method (Shimadzu, Kyoto, Japan). The difference in concentration between the fumigated and unfumigated samples, corrected for C evolved as CO_2, was used to calculate the microbial biomass C (Brookes et al., 1985; Jørgensen, 1995, 1996). Soil pH was determined on fresh soil samples using a 1:5 w/v ratio with milliQ water, followed by 30 minutes of shaking. Air-dried soil samples were used for Olsen P analysis, following the method described by Murphy and Riley (1962) and Olsen et al. (1954). The samples were extracted using a 0.5 M $NaHCO_3$ solution at a 1:20 w/v ratio with 30 minutes of shaking, and the pH was adjusted to 8.5. The extracts were then filtered using Whatman No. 42 filter paper. The SEAL Autoanalyser AA3 (Seal Analytical, Fareham, UK) was used to analyse the extracted samples based on the molybdenum blue colorimetric reaction (Method No G-103-92 Rev1; Multitest MT7/MT8). Soil dry matter (DM) and loss on ignition (LOI) were determined using a gravimetric method. Approximately 12 g of fresh soil was oven-dried at 105°C for 48 hours to obtain the dry weight (DW). Subsequently, around 1.5 g of the oven-dried soil was heated at 550°C for 6 hours in a muffle furnace, cooled overnight, and weighed to determine the LOI. The TC and TN content of the soils were determined using an automated Dumas procedure on a Carbo Erba NA 1500 analyser (Erba Science, Surrey, UK), with 30 ± 1 mg of oven-dried and ball-milled soil. Fresh soil samples were also extracted for available nitrogen (NH_4^+-N and NO_3^--N) using 1 M KCl at a 1:5 w/v ratio with 1 hour of shaking, as described by Bremmer (1965) and McTaggart & Smith (1993). The extracts were filtered using Whatman No. 42 filter paper, and the filtrate was subsequently analysed for NH_4^+ and NO_3^- content using the SEAL autoanalyser AA3 with two different colorimetric reactions (Method No G-102-93 Rev 2; Multitest MT7/MT8).

4.2.8 Statistical analysis

Linear mixed models and the Kenward Rogers method procedure was used to explore how soil samples treated with different amendments vary over time (0, 1, 3, 7, 14, 28, 56, and 90 days). Kenward-Roger method, a statistical technique used to calculate degrees of freedom in linear mixed-effects models, enhancing the accuracy of hypothesis tests and p-value calculations, especially in situations where the model's structure is intricate or unbalanced (Kreidler et al., 2021). The fixed factors were the type of amendment (Safisana, Cockerham Green, NP and Control) and the incubation time (0, 1, 3, 7, 14, 28, 56, and 90 days). To further examine significant differences in the main effects, Tukey method was used for pairwise comparisons on the shape of the curve. All analyses were performed in triplicate using either fresh or dry soil samples. Statistical analyses were performed with R studio (R Core Team, 2019), version 2022.07.1 + 554) with ggplot2 (Wickham, 2016), agricolae (Mendiburu and Yaseen, 2020), ggpubr (Kassambara, 2020), ggfortify (Tang et al., 2016) and corrplot (T. aiyun Wei and Simko, 2021) packages used.

4.3 Results and Discussions

4.3.1 Effects of Fertilising material on soil pH

Soil pH is a crucial factor affecting nutrient availability, microbial activity, and overall soil health. Over the 90-day period (Figure 4.1), the study observed a discernible general decline in soil pH levels upon the application of fertilisers. The pH values for sandy Podzols fluctuated between 6 and 7 at the onset (day 0) and exhibited a narrowing range over the course of the study, whereas Ferric Acrisol showed a slightly more acidic range, from 5.7 to 7 initially.

A higher dose of fertilisers, specifically at a rate of 90 kg N/ha, manifested a pronounced decrease in soil pH across both soil types. Statistical analysis revealed that this decline was significant ($p < 0.05$), underscoring the impact of the fertilising materials used namely NP and Safisana. In particular, sandy Podzols treated with Cockerham Green experienced a reduction in pH from 6.85 to 6.31, while NP application resulted in a shift from 6.9 to 6.1. Comparable significant reductions were evident in Ferric Acrisol with Cockerham Green and NP amendments leading to a decrease in soil pH from 6.55 ± 0.1 to 5.58 ± 0.1 and from 5.75 ± 0.3 to 5.47 ± 0.3, respectively. Similarly, Safisana's application culminated in a decline from 6.34 ± 0.4 to 5.3 ± 0.14.

The mechanism underlying soil acidification can be attributed to the application of urea and NH_4^+ rich fertilisers such as manure and digestate (Galamini et al., 2023). The hydrolysis of urea in the soil forms ammonia and CO_2, with ammonia subsequently converting into ammonium, thereby contributing to soil acidification (Afshar et al., 2018). Initial production of a basic ion by urea is rapidly followed by nitrification, a process during which the transformation of ammonium to nitrate releases protons, thus lowering the soil pH (Klimczyk et al., 2021). Digestates may further exacerbate this effect due to their content of organic acids and capacity to release ammonium, which, through subsequent nitrification and mineralisation, yields an additional proton load. This acidifying trend is influenced by a multitude of factors, including the soil's inherent buffering capacity, initial pH, and its moisture and aeration status.

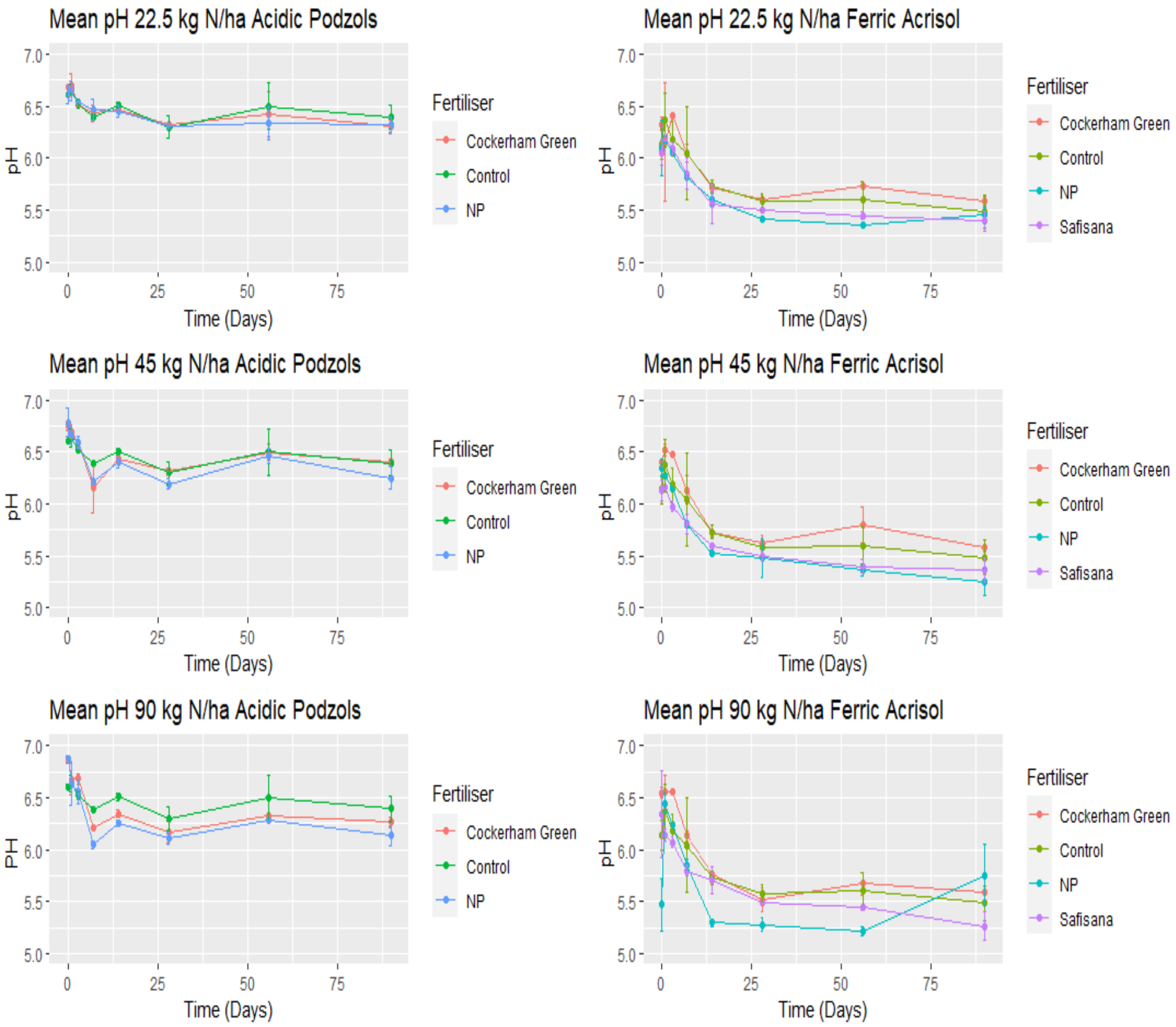

Figure 4.1 Effects of Fertilising material on soil pH (Symbols represent means ± SD of 3 replicates)

4.3.2 Effects of Fertilising material on soil Electrical Conductivity

Electrical conductivity (EC) in soil is a measure of the soil's ability to conduct electrical current, which is closely linked to the concentration of dissolved ions (salts) in the soil solution (Martinez et al., 2021). EC is an indicator of nutrient availability in the soil, as it reflects the presence of dissolved salts. The introduction of fertilisation materials has been observed to augment the EC values throughout a span of 90 days (Figure 4.2). Within the context of Ferric Acrisol, the application of Safisana escalated the EC from 50.4 ± 6.42 to 140.6 ± 16.6, showcasing a statistically significant enhancement ($p < 0.05$). Similarly, NP's application elevated the EC from 52.3 ± 5.7 to 189 ± 7.09, indicating a significant rise ($p < 0.05$). The application of Cockerham Green increased the EC from 50.4 ± 5.0 to 135.4 ± 6.4, alongside the unamended soil, which saw an increase from 39.33 ± 4.0 to 132.83 ± 5.01, both demonstrating significant differences ($p < 0.05$). Moreover, in sandy Podzols, Cockerham Green's EC rose from 64.72 ± 1.87 to 123.83 ± 16.9, NP from 56.3 ± 1.7 to 117.83 ± 7.17, and NP alongside unamended soil from 51.63 ± 0.3 to 85.43 ± 4.8, all evidencing significant differences ($p < 0.05$).

The underlying mechanism for this EC increases attributes to the additional ions introduced by these materials, consequently influencing the soil's ionic strength. A comparative analysis of dose-response trends across different soil types revealed no significant difference in *Ferric Acrisol* treatments, barring the comparison between Cockerham Green and NP at a 22.5 kg N/ha dosage. At a 45 kg N/ha dosage, significant differences were observed between (i) Control and NP, and (ii) Cockerham Green and NP, whereas a significant variance ($p \leq 0.05$) emerged in the treatments between NP and Safisana, NP and Cockerham Green, and NP and Control at a 90 kg N/ha dosage.

However, no significant differences ($p > 0.05$) were discernible between Cockerham Green and Control, Cockerham Green and Safisana, and Control and Safisana.

In sandy Podzols, treatments exhibited no significant differences, except between NP and Control at a 22.5 kg N/ha dosage. At a 45 kg N/ha dosage, only (i) NP and Control displayed a significant difference ($p > 0.05$). At a 90 kg N/ha dosage, significant differences were noted between Cockerham Green and Control, and NP and Control, with no significant differences ($p > 0.05$) observed between Cockerham Green and NP.

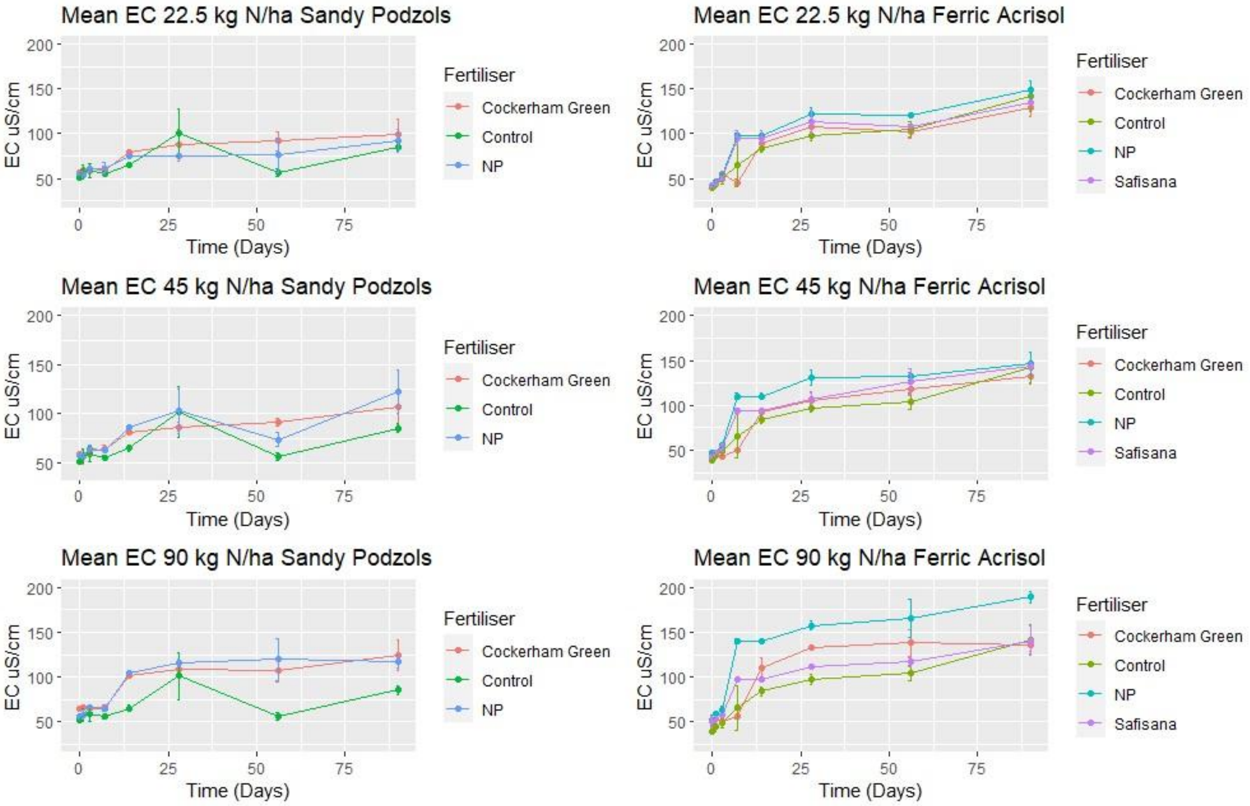

Figure 4.2 Effects of Fertilising material on soil Electrical Conductivity (Symbols represent means ± SD of 3 replicates)

These findings are paralleled in the hydrolysis of urea within soil, which supports the ionic strength and consequently the EC. The decomposition of urea results in the formation of ammonium ions (NH_4^+), contributing to the EC's elevation. Digestate, as a by-product of anaerobic digestion, harbours a considerable mineral content, enriching the soil EC upon its application. This aligns with Sheng et al. (2023) who assert that long-term bio-organic fertilisation maintains soil EC, accompanied by substantial alterations in soil chemical properties following prolonged fertilisation treatments. Zireeni et al. (2023) corroborate these findings, observing a general EC increase under the influence of acidified and non-acidified slurry in a controlled study spanning over 50 days.

4.3.3 Effects of Fertilising material on soil Available Nitrogen

4.3.3.1 Ammonium Nitrogen

The application of fertilising materials to soil is a pivotal agricultural practice, enhancing nutrient availability and promoting plant growth (Ishfaq et al., 2023). Among these nutrients, ammonium nitrogen (NH_4^+-N) plays a critical role due to its direct assimilation by plants. When fertilisers are added to the soil, NH_4^+-N content typically increases, reflecting the conversion of applied nitrogenous compounds into forms accessible to plants. This process can significantly influence the nitrogen cycle within soil ecosystems, affecting both plant health and agricultural productivity (Liu et al., 2022).

The investigation into the influence of fertilisation materials on soil-available nitrogen, specifically focusing on ammonium nitrogen (NH_4^+-N) levels, revealed distinct variances across different soil types. Sandy Podzols demonstrated comparatively lower

NH_4^+-N concentrations, recording at 10 mg/kg, whereas Ferric Acrisol exhibited a broader range of 20 to 40 mg/kg. This disparity underscores the soil type's role in nutrient dynamics following fertiliser application.

In Ferric Acrisol, an incremental increase in fertiliser dosage was directly correlated with augmented NH_4^+-N levels. The temporal pattern of NH_4^+-N concentration exhibited an initial surge within the first three days post-application, succeeded by a reduction from day 3 to day 14, and a subsequent decline persisting until day 90. This trend is attributed to diminishing detection rates over time. For instance, under a 22.5 kg N/ha treatment in Ferric Acrisol, NH_4^+-N levels were recorded as follows: 12.1 ± 0.13 mg/kg at Day 0, peaking to 25.89 ± 0.03 mg/kg by Day 3, then declining to 8.145 ± 8.8 mg/kg by Day 90. Similar trends were observed at higher fertilisation rates, with notable fluctuations in NH_4^+-N concentrations.

A comprehensive statistical analysis elucidated significant disparities in NH_4^+-N levels between various treatments and control groups, particularly within sandy Podzols. At 22.5, 45, and 90 kg N/ha dosages, significant differences ($p \leq 0.05$) were discerned between NP and Control treatments, highlighting the impact of fertilisation on ammonium nitrogen availability. Conversely, comparisons between Cockerham Green and the control group, as well as between Cockerham Green and NP at 22.5 and 45 kg N/ha, did not manifest significant variations ($p > 0.05$). Nevertheless, a notable difference ($p \leq 0.05$) emerged at the 90 kg N/ha dosage.

In contrast, Ferric Acrisol's response to fertilisation was characterised by a lack of significant differences ($p > 0.05$) between Cockerham Green and the control group, as well as between Cockerham Green and NP across all examined treatments. However, at a 45 kg N/ha dosage, a marginal yet statistically significant difference ($p = 0.05$) was observed between NP and Safisana, indicating nuanced effects of fertiliser types on ammonium nitrogen levels. Furthermore, at dosages of 22.5 and 90 kg N/ha, significant differences ($p \leq 0.05$) were recorded between Cockerham Green and the control group, with a marginal significant distinction ($p = 0.05$) also being noted between NP and Safisana at the 90 kg N/ha treatment, underscoring the complex interplay between fertiliser type, dosage, and soil nutrient dynamics.

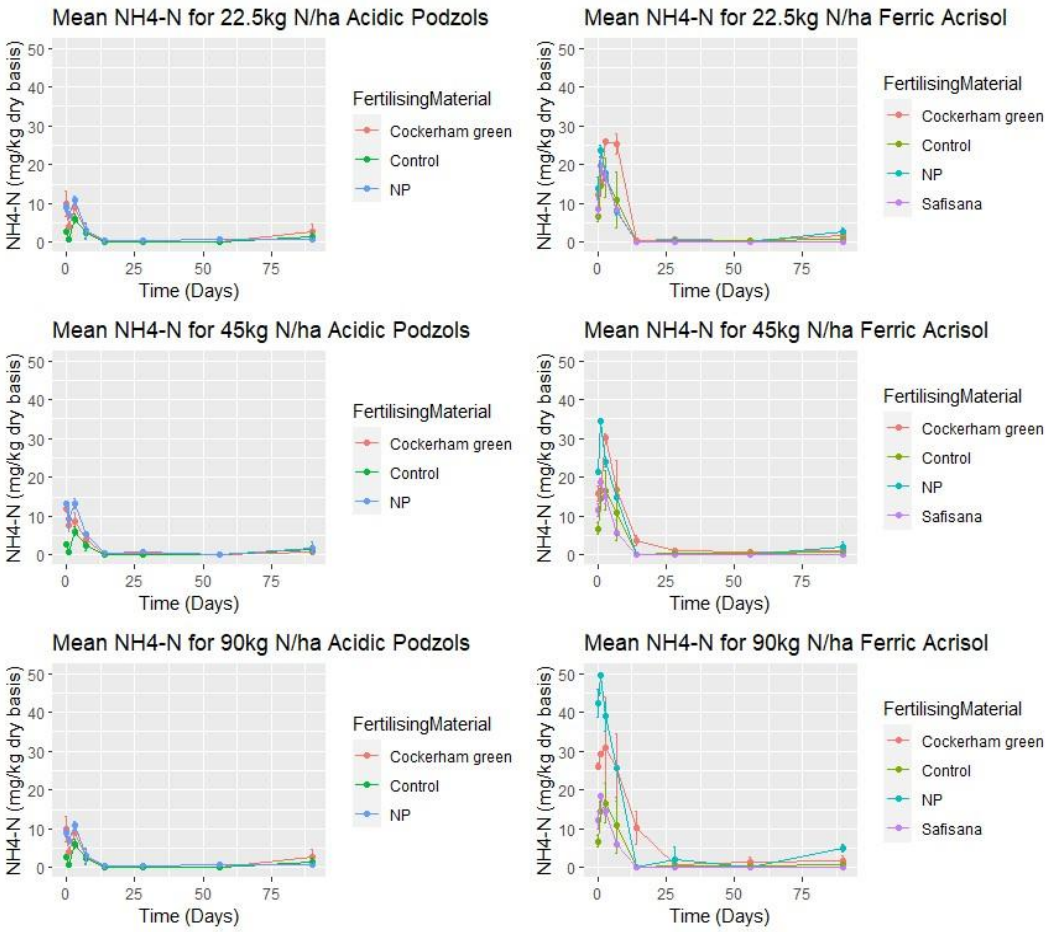

Figure 4.3: Effects of Fertilising material on soil Ammonium Nitrogen (Symbols represent means ± SD of 3 replicates)

4.3.3.2 Nitrate Nitrogen

Assessing the conversion of nitrogen to nitrate (NO_3^--N) in soils under different treatments revealed a consistent pattern across all treatment levels, characterised by an initial rise in nitrate concentration within the first three days, followed by a reduction and stabilisation phase extending from day 7 to day 90. The experimental framework considered the response to different nitrogen application rates from various fertilising materials on two soil types, namely *sandy Podzols* and *Ferric Acrisol*. These rates were categorised as 22.5 kg N/ha (yielding nitrate levels between 0.25 to 12.5 mg/kg), 45 kg N/ha (2.5 to 15 mg/kg), and 90 kg N/ha (2.5 to 20 mg/kg). Although the starting NO_3^--N in sandy Podzols were 3.7 ± 1.1 mg/kg whiles that of Ferric acrisol were 2.4 ± 0.4 mg/kg. The findings indicated that *sandy Podzols* demonstrated lower nitrate concentrations compared to *Ferric Acrisol*, suggesting an inherent background nitrogen present in *Ferric Acrisol*. Another interpretation could be that there was low microbial activity hence there was not much change in the rate of NO_3^--N.

Furthermore, the study assessed the impact of different fertilising materials on soil nitrate levels. Among the fertilisers evaluated, the NP treatment resulted in the highest nitrate concentrations, followed by Cockerham Green and Safisana fertilisers, across all application rates. However, nitrate levels remained relatively low regardless of the fertiliser application rate. A rigorous statistical analysis (as detailed in the study's appendix) identified significant differences ($p \leq 0.05$) between the control group and both the Cockerham Green and NP treatments. In contrast, no significant differences ($p > 0.05$) were noted between the Cockerham Green and NP treatments. These results imply that the introduction of fertilising materials to the soil incurs notable temporal changes in nitrate levels, a trend not observed in the unamended soils of *sandy Podzols*.

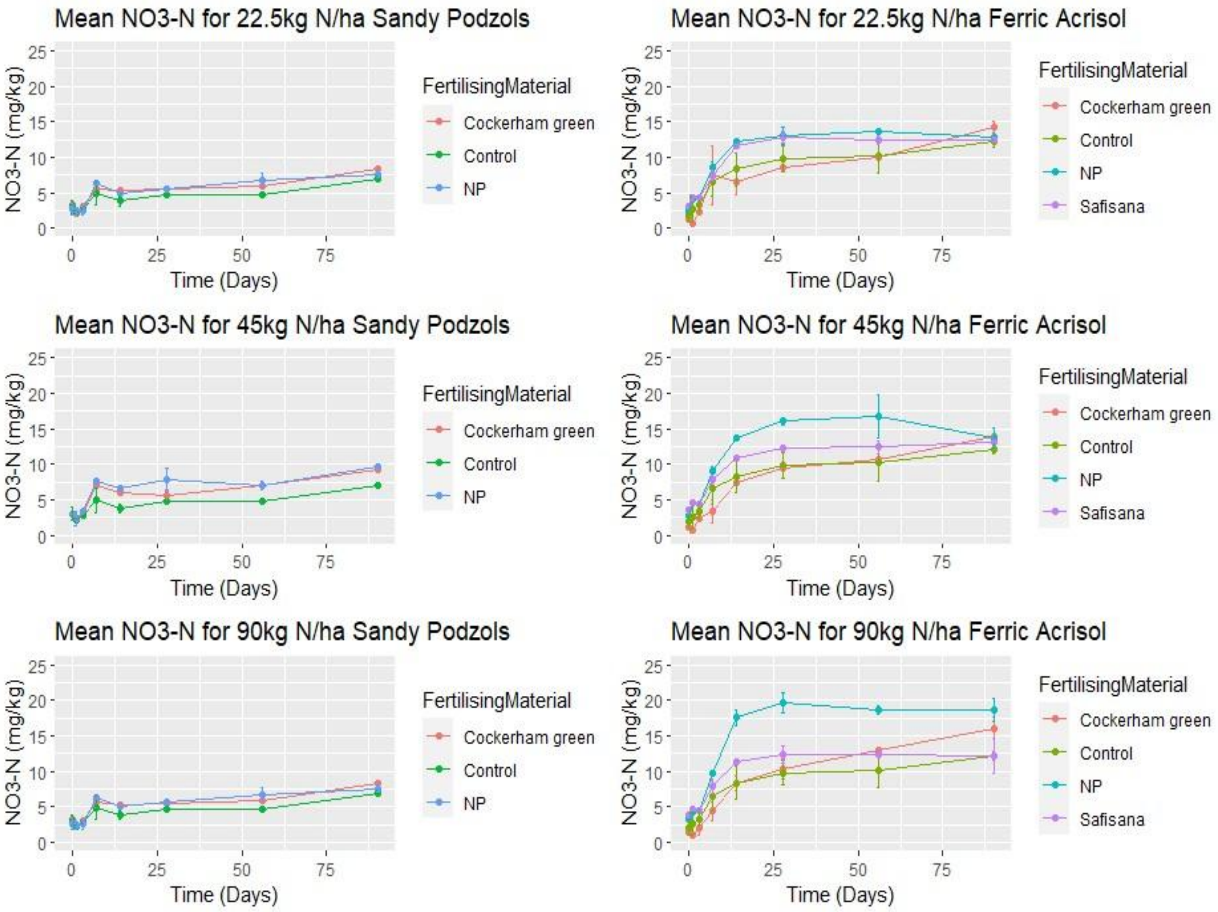

Figure 4.4 Effects of Fertilising material on soil Nitrate Nitrogen (Symbols represent means ± SD of 3 replicates)

In analysing nitrate levels in soil, several key findings emerged from the statistical analysis. There was a small amount of residual variability within replicates, with a mean square of 0.03793 indicating variation within replicates not explained by other factors. The variability in nitrate levels among different treatments was statistically significant ($p \leq 0.05$). Treatment showed a strong effect ($F = 74.41$, $p < 0.001$) in *sandy Podzols* by nitrate levels. The variability in nitrate levels among different fertiliser amounts was also significant ($p \leq 0.05$). The F value for fertiliser added was 58.87, with a p-value of 0.07805, suggesting a non-significant effect ($p>0.05$). The interaction between treatment and the amount of fertiliser added was not significant, with an F value of 16.92 and a p-value of 0.42394. The factor of time emerged as highly significant ($p \leq 0.05$) in affecting nitrate levels, with a $p < 0.05$, indicating substantial changes in nitrate concentrations over time. Notably, no significant interactions ($p > 0.05$) were observed between the treatment and the amount of fertiliser added over the study period. In *sandy Podzols*, significant differences ($p \leq 0.05$) were noted between the CG and control treatments, as well as between NP and control treatments, particularly at the 45 kg N/ha and 90 kg N/ha levels. For *Ferric Acrisol* soils, notable differences were observed between Cockerham Green and control, Cockerham Green and NP at 22.5 kg N/ha, and across various treatments at 45 kg N/ha. However, at 45 kg N/ha, no significant differences ($p > 0.05$) were detected between Cockerham Green and Safisana treatments.

The study also recognised that the effects of Cockerham Green and NP fertilisers on soil dynamics were influenced by several factors, including initial soil properties, moisture, and temperature. The addition of fertilising materials enriched the soil with available nitrogen, a critical element for plant growth. In the context of unplanted soils, the nutrients tended to accumulate over time due to their non-utilisation. Furthermore, the nitrogen presents in digestate, and urea fertilisers likely underwent processes of mineralisation and immobilisation by microorganisms. Thus, the balance between these processes could have influenced availability of nitrogen in the soil. Additionally, soil organic matter decomposition, facilitated by microbial activity, released nitrogen in the form of ammonium (NH_4^+), which was eventually converted to nitrate through nitrification, leading to its accumulation (Shahbaz et al., 2017). Again, the use of nitrogen-containing fertilisers such as urea (NP) likely contributed to increased nitrate concentrations, as nitrate in these fertilisers is readily available for nitrification and uptake by soil microbes (Norton and Ouyang, 2019). In the absence of plants, which are primary consumers of nitrate, a continuous conversion of ammonium to nitrate was observed over the 90-day incubation period. Results from the experiment emphasised the complex interplay of various factors in determining nitrate dynamics in soil ecosystems (Liu et al., 2021).

4.3.4 Effects of Fertilising material on soil Olsen P (Available P)

No significant differences ($p < 0.05$) were noted in the outcomes of Olsen P levels for all treatments when 45 and 90 kg N/ha were applied although application of 90kg N/ ha accompanied a higher application rate of P at 45kg P/ha (Figure 4.5).

Regarding *Ferric Acrisols*, discernible differences were identified between the NP) and Safisana treatments, NP and Control, NP and Cockerham Green, Safisana and Control, and Safisana and Cockerham Green. However, no significant difference was observed between CG and Control for the 22.5 kg N/ha dose. Additionally, at higher doses of 45 kg N/ha and 90 kg N/ha, no notable differences were detected. In the context of *sandy Podzols*, adding fertilisers did not significantly alter the levels of extractable P (inorganic phosphorus). This was consistent across all tested doses in our study, specifically 22.5 kg N/ha, 45 kg N/ha, and 90 kg N/ha (Figure 4.5). The observation of no significant difference observed can be attributed to several factors.

Firstly, soils have a natural buffering capacity for phosphorus, meaning they can absorb or release P to maintain a certain level of available P. In soils with high buffering capacity, the addition of small amounts of phosphorus may not significantly alter the equilibrium, making the added P less available. Again, soils often contain minerals that can bind with P, making it unavailable to plants. This process, known as P fixation, is particularly prevalent in low pH soils with high contents of Fe and Al oxides (as in *Ferric Acrisol*) or calcium (in calcareous soils) (Asrade et al., 2023). The P added through low-dose fertilisation can quickly become fixed and, therefore, not contribute to the available P pool (Pizzeghello et al., 2011). Thus, soil pH can also affect the availability of P for plant uptake (Penn and Camberato, 2019) although does not apply. Furthermore, some P fertilisers release P slowly over time. If the rate of release is slow and the dosage is low, there may not be a sufficient increase in the available P in the short term. Additionally, soil microbes play a role in phosphorus cycling, potentially immobilising some of the added P. These biological activities can quickly utilise or immobilise the added P, especially if the fertiliser dose is low. Finally, factors such as moisture, temperature, and aeration can influence the effectiveness of P fertilisers. Soluble P can be lost through deep leaching in some situations or soil surface runoff (Roberts and Johnston, 2015; Yahaya et al., 2023). Although we did not anticipate leaching in our experiment, there may be a chance P percolated to the bottom of the sample bottles. In certain conditions, the added phosphorus might not be readily available to plants.

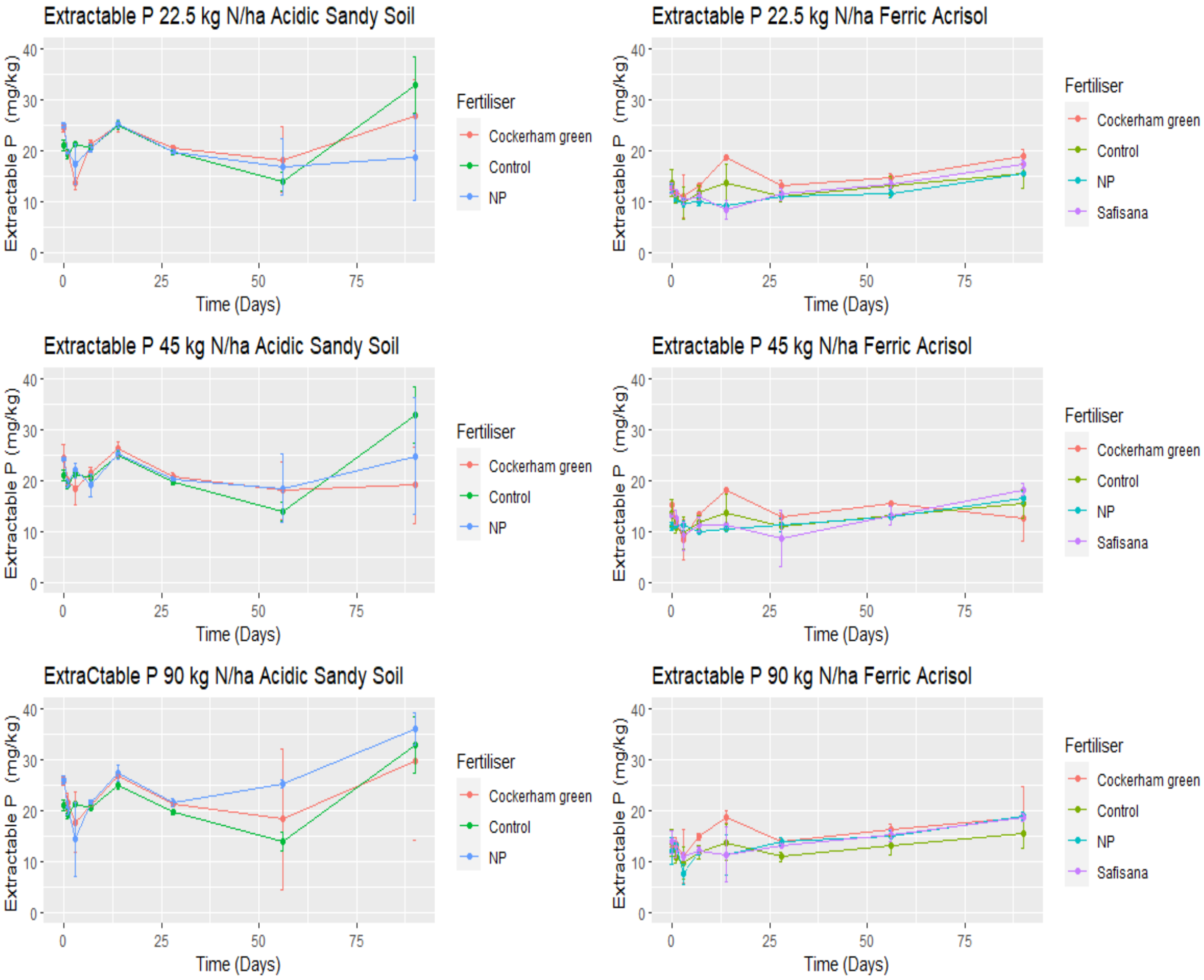

Figure 4.5 Effects of Fertilising material on Extractable P (Symbols represent means ± SD of 3 replicates)

The level of Olsen P did not significantly differ in *sandy Podzol*, since these soils typically have a coarse texture with large pore spaces, leading to high drainage and leaching potential. When low doses of P fertilisers are applied, much of the P can be leached away from the root zone before plants can utilise it, especially in over irrigation for controlled experiments like ours of heavy rainfall in field conditions. The sandy nature of Podzols means they have a low capacity to hold nutrients, including P. This is due to the low levels of clay and organic matter in such soils, which are crucial for nutrient retention. Again, in sandy soils, the rapid mineralisation of organic matter and subsequent immobilisation of nutrients by soil microorganisms can quickly transform added P into forms that are not readily available to plants. Lastly, the availability of P in soils is greatly affected by pH levels. *Sandy Podzols* can sometimes be acidic, and in such conditions, P becomes less available due to its tendency to form insoluble compounds with iron and aluminum (Muhammad et al., 2022). In planted conditions podzols can restrict crop growth and productivity (Muhammad et al., 2022).

The solubility of phosphorus is highly dependent on soil pH. In acidic soils (pH < 5.5), P can become fixed with iron and aluminium, forming compounds that are not readily available to plants. Conversely, in alkaline soils (pH > 7.5), P can precipitate with calcium, also reducing its availability. The decline in pH that you have observed, especially if it moves towards these critical pH levels, could potentially increase the risk of phosphorus fixation, depending on the soil's mineral composition.

Microbial processes are highly sensitive to changes in pH (Crowley and Alvey, 2002). Microbes play a crucial role in the transformation of organic P compounds into forms that plants can uptake (Pang et al., 2024). A significant change in pH could alter microbial communities and their activities, influencing the rate at which P is mineralised or immobilised.

The pH influences the ionic state and the charge balance of various compounds in the soil (Mc Bride, 1989). As pH decreases, the availability of positively charged ions (cations) that can interact with phosphate ions may increase, potentially leading to more phosphorus being bound to soil particles and less remaining in a soluble form for plant uptake (Barrow and Hartemink, 2023).

Given these points, the significant pH changes over the 90-day period in our study may influence the availability of extractable P measured as Olsen P. If the pH has significantly decreased, it could result in greater P fixation in soils with a high content of reactive Fe and Al oxides, like Ferric Acrisol, although this will also depend on the buffering capacity of the soil to resist changes in pH (Sanchez, & Uehara, 1980). In sandy soils, which typically have a lower buffering capacity and may be less prone to P fixation, changes in pH might not have as pronounced an effect on Olsen P levels.

4.3.5 Effects of Fertilising material on soil Microbial Biomass Carbon

Microbial biomass is the measure of the mass of living component of soil organic matter (Brookes, 2001). The microbes decompose plant and animal residues and soil organic matter to release carbon dioxide and plant available nutrients. The MB is influenced by pH, moisture, clay content and availability of organic carbon (Rakhsh et al., 2020). MB is a significant source of N hence the death of MB releases nutrient in the form that can be taken by plants.

In the Sandy Podzols (Figure 4.6), the MBC was generally lower across all treatments compared to Ferric Acrisol. At the lowest N application rate (22.5 kg N/ha), the MBC values were relatively stable over time for all fertiliser treatments, showing minimal fluctuations. The Control and NP treatments maintained a relatively constant MBC, suggesting limited impact from these treatments on microbial activity at this N rate.

At higher N rates (45 kg N/ha and 90 kg N/ha), a decreasing trend in MBC was observed, particularly evident in the Cockerham Green and NP treatments. This reduction could suggest that higher N concentrations might be inhibitory to microbial populations or alter microbial community dynamics in Sandy Podzols.

Contrary to Sandy Podzols, Ferric Acrisol showed more variability in MBC across treatments, especially at the lowest N application rate. Safisana treatment displayed a significant increase in MBC at around 25 days, which could indicate a beneficial interaction between this fertiliser and soil microbes that enhances microbial carbon sequestration or utilisation. As the N application rate increased to 45 kg N/ha and 90 kg N/ha, all treatments, including the control, tended to converge towards similar MBC values by the end of the monitoring period.

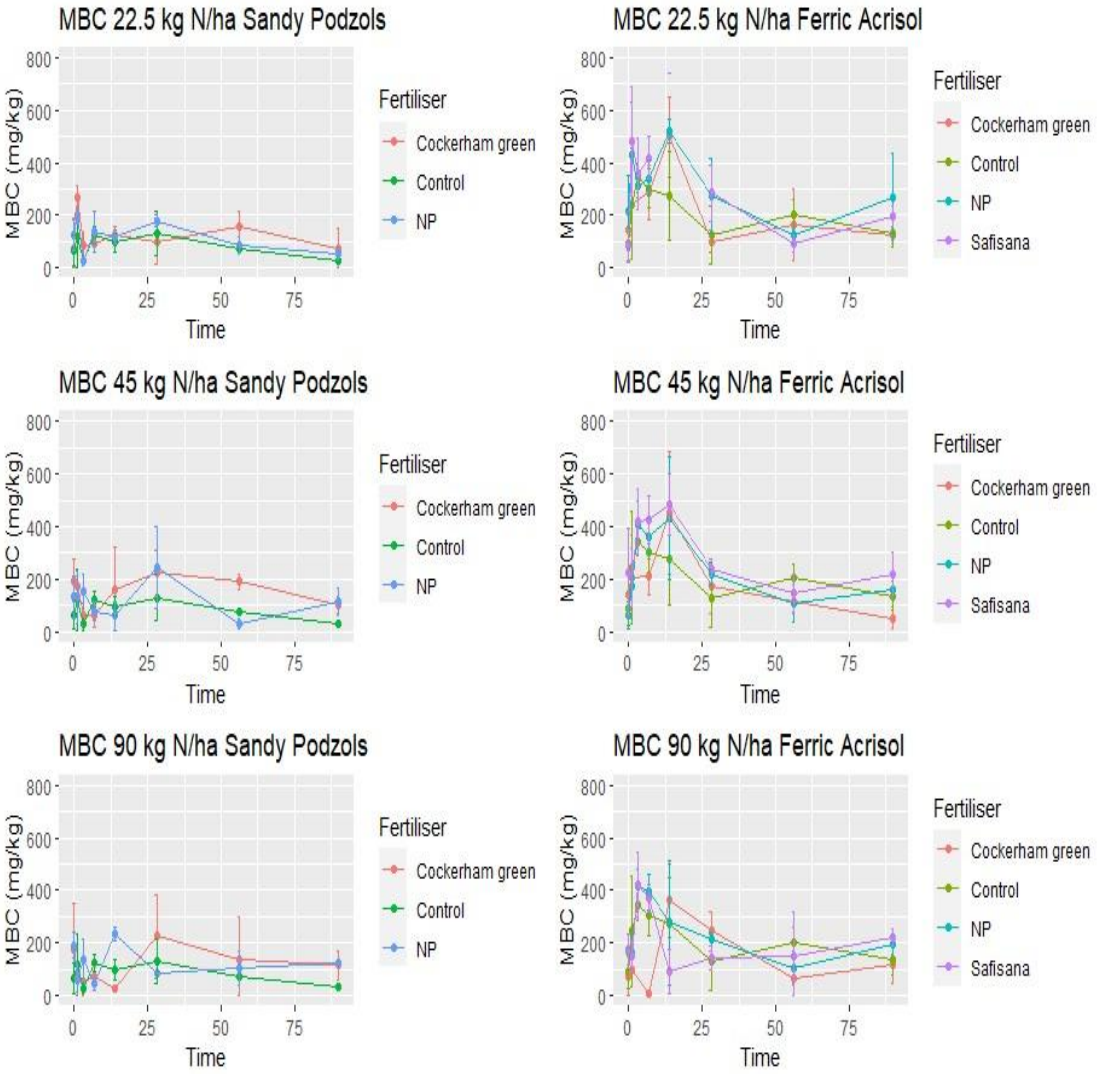

Figure 4.6 Effects of Fertilising material on soil Microbial Biomass Carbon (Symbols represent means ± SD of 3 replicates)

This suggests a potential threshold effect where beyond a certain nutrient input level, MBC stabilisation occurs regardless of the fertiliser type. The differing responses between soil types and treatment could be due to inherent soil characteristics, such as texture, organic matter content, and initial microbial community structure, which influence nutrient dynamics and microbial processes. The apparent stabilising effect of higher N rates on MBC in Ferric Acrisol might indicate a saturation point where additional N does not significantly alter microbial biomass.

These results underscore the complex interactions between soil type, fertiliser composition, and N rates in influencing soil microbial communities, which are crucial for nutrient cycling and soil health. The reduction in MBC at higher N rates in Sandy Podzols could also have implications for soil carbon storage and fertility over the long term. Overall, these findings highlight the importance of considering soil-specific management practices when applying fertilisers to optimise microbial health and nutrient efficiency.

4.3.6 Effects of Fertilising material on soil Microbial Biomass Nitrogen

In sandy Podzols (Figure 4.7), no visible trend was observed in the first 28 days for the 22.5 kg N/ha dosage. The addition of Cockerham Green digestate recorded a high microbial biomass nitrogen (MBN), followed by NP and Control. For the 45 kg N/ha dosage, Cockerham Green recorded a higher MBN after variability in the first 14 days, followed by NP and Control. In the 90 kg N/ha treatment, MBN showed high variability in the first 28 days. Again, Cockerham Green exhibited high MBN compared to NP and Control (unamended soil).

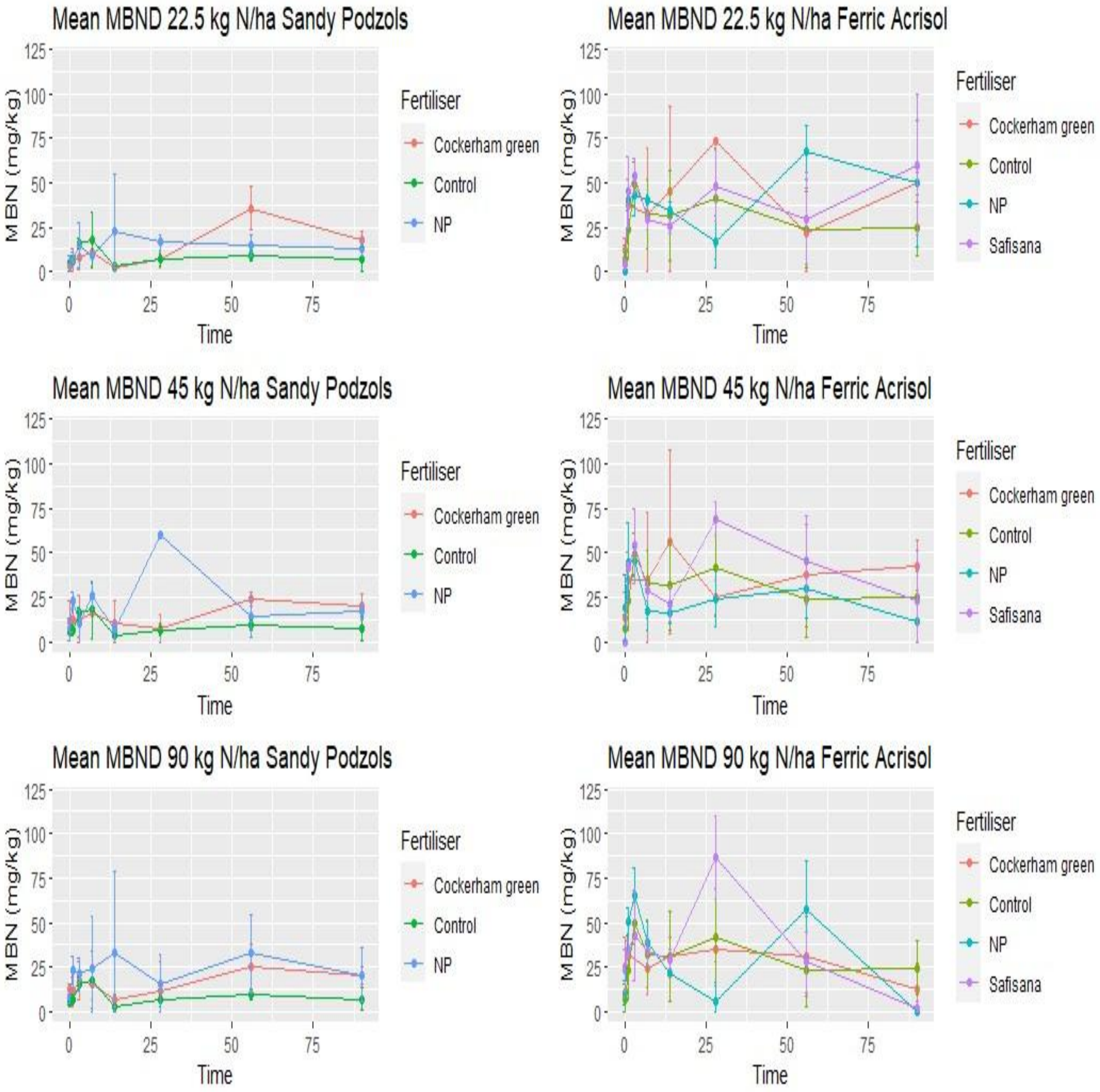

Figure 4.7 Effects of Fertilising material on soil Microbial Biomass Nitrogen (Symbols represent means ± SD of 3 replicates)

Higher MBN was observed on day 28 for all treatments in the sandy Podzols. Microbial biomass is the measure of the mass of the living component of soil organic matter, decomposing plant and animal residues and soil organic matter to release carbon dioxide and plant-available nutrients. Microbial biomass (MB), influenced by pH, moisture, clay content, and availability of organic carbon, is a significant source of nitrogen; hence, the death of MB nutrients in a form that can be absorbed by plants.

4.3.7 Effects of Fertilising material on soil Microbial Biomass Phosphorus

The addition of phosphorus (P) to soil did not significantly impacts microbial biomass phosphorus (MBP) over a 90-day period under ideal conditions of soil moisture and temperature. Although time had a significance effect on the MBP for all doses and soil type, no significant differences was observed for, 22.5 kg N/ha, 45 kg N/ha, 90 kg N/ha, for *sandy Podzols*. However, we did find some significant effect at 45 kg N/ha between CG and Control, CG and NP (45 kg N/ha, 22.5 kg N/ha) and CG and Safisana (45 kg N/ha) in *Ferric Acrisol*. The effect varies depending on soil properties, the existing microbial community, and the form and amount of P added.

Initially, in the first 30 days, there's an increase in microbial activity as P availability allows for the proliferation of microbes previously limited by P scarcity. This can lead to changes in the microbial community's composition, favouring taxa that efficiently uptake and utilise P. Phosphorus is vital for all living organisms, including soil microbes, as it is a key component of ATP, nucleic acids, and phospholipids, crucial for energy transfer, genetic information processing, and cell membrane integrity. Microbes that can efficiently absorb and use P are likely to become more dominant. However, from 60 to 90 days, there may be a saturation effect, leading to a plateau or decline in microbial activity.

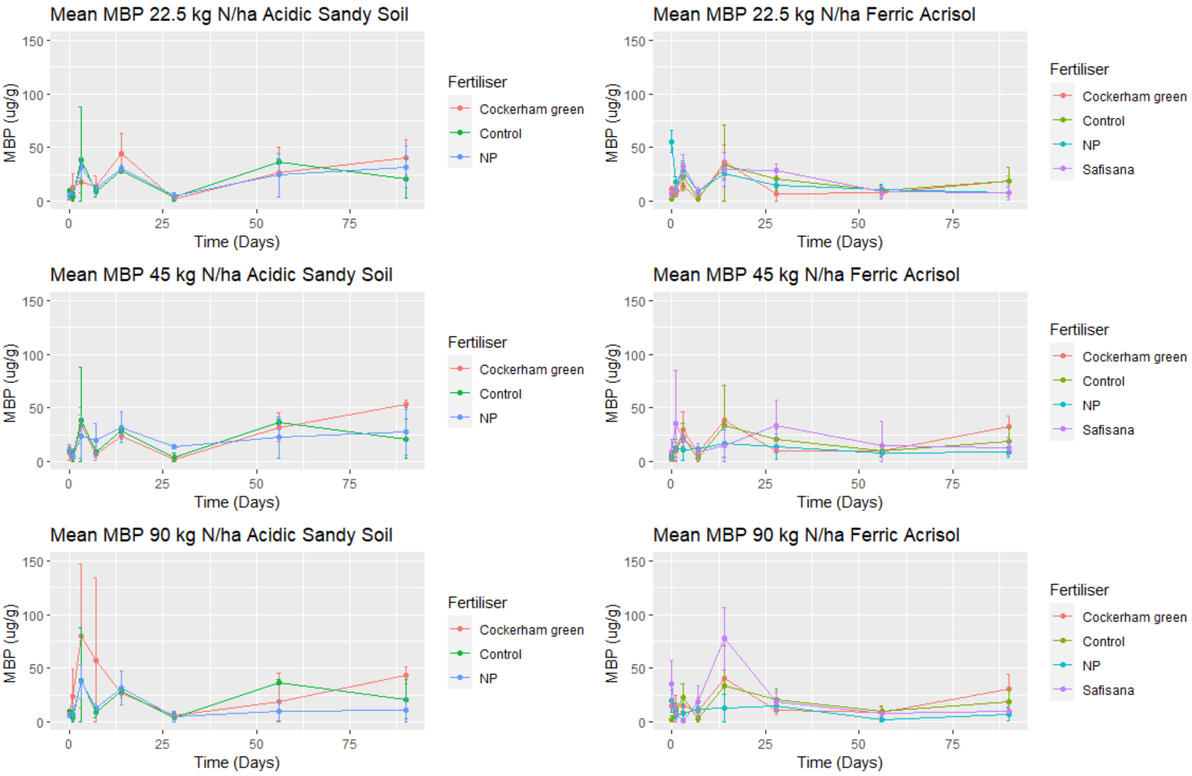

Figure 4.8 Effects of Fertilising material on MBP (Symbols represent means ± SD of 3 replicates)

This could be due to other nutrient limitations (like N or K), immobilisation of P into unavailable forms, or the microbial biomass reaching its environmental or biological carrying capacity. Different soils respond differently to P additions. Soils with initially low P levels are more likely to show a significant response to added P and an increase in MBP.

4.4 Conclusion

This study highlights the complex interaction between soil types, fertilisation practices, and nutrient dynamics. Specifically, the application of different fertiliser s, including digestate and mineral fertiliser s, has distinct impacts on soil properties such as electrical conductivity (EC), nitrogen (N) conversion to nitrate (NO_3^--N), and Olsen P levels. Fertilisation significantly influences soil EC, with organic and inorganic fertilisers introducing additional ions into the soil, thereby affecting its ionic strength. However, the response of soil to fertilisation, in terms of nutrients like phosphorus and nitrogen, varies considerably between soil types (e.g., *Ferric Acrisol* and *sandy Podzols*) and depends on the rate of fertiliser application. The microbial biomass (MB) plays a crucial role in decomposing plant and animal residues, thus releasing essential nutrients in forms available to plants. The dynamics of microbial biomass phosphorus (MBP) and its variability under different fertilisation rates highlight the microbial response to soil management practices. The conversion of nitrogen to nitrate and the availability of phosphorus (P) in soils are significantly influenced by fertilising material addition. However, factors such as soil type, initial soil properties, moisture, temperature, and soil's buffering capacity for P greatly determine the extent of these nutrients' availability and cycling within the soil ecosystem. The inherent properties of soil types, such as *Ferric Acrisol* and *sandy Podzols*, influence their response to fertilisation. While *Ferric Acrisol* shows a more pronounced response in nutrient levels to fertilisation, *sandy Podzols* exhibit less variability, indicating the influence of soil characteristics on nutrient dynamics. Environmental factors such as pH, moisture, clay content, and the availability of organic carbon are critical in determining the effectiveness of fertilisation. These factors not only influence microbial biomass but also affect the cycling and availability of essential nutrients like N and P.

4.5 Supplementary Information for Chapter 4

4.5.1 Microbial Biomass Nitrogen (MBN)

Amount of MBN was higher in *Ferric Acrisols* than Podzols. Values ranged from 0 -75 mg/kg in *Ferric Acrisol* whiles values range from 0 -40 for 22.5 kg N/ ha, 0-63 mg/Kg for applications of 45 kg N/ ha, 0 -75 mg/kg for applications of 90 kg/N ha in *sandy Podzols*. MBN did not follow a any pattern as there was a rise and fall in graphs. There was no confirmative pattern in the MBN for both soil types indicating that there was an activity, but the activity was not affected by the treatments of the Fertilising material nor dependent on the soil type. To investigate if the different fertilising material and application rates has any significant impact on Microbial Biomass Nitrogen on *Ferric Acrisol* or *sandy Podzols*, we used a loess trend to show any obvious patterns. We also superimposed linear trends to assess the strength of linear relationships. A symbolic representation of the linear model used is Equation 1 to show whether there is interaction between time and fertilising material to reveal possible trends for different fertilising material.

Call

Amount of MBND in soil = β_0 + β_1 * time …………….equation 1

Where β_0 = intercept of the fertilising material

β_1 = fertilising material

Figure S41 shows the results for fertilising material (NP, Safisana, CG) and Control. The lines are the model results from equation 1. The fitted model for Fertilising material (NP, Safisana, CG) and Control is show in Figure S41 1. The hypothesis tests if different fertilising material and application rate has a significant effect on MBN in Sandy Podzols. The dependent variable MBN was regresses on the predicting variable different fertilising material and application rates to test the H1. The Microbial Biomass Nitrogen did not significantly predict the different fertilising material and application rate. F (3, 164) = 3.243, p< 0.02353 which indicated that the Microbial Biomass Nitrogen does not play a role in shaping MBN (B = - 0.08247 (Control), 0.09958 (CG), 0.11838 (NP), p< 0.0001. The results clearly do not direct positive effect of DFMAR on Microbial Biomass Nitrogen. Moreover, the $R^2 = 0.02353$ depicts that the model explains 2.353% of the variance in MBN.

The table 10 and 11 shows the summary of the findings.

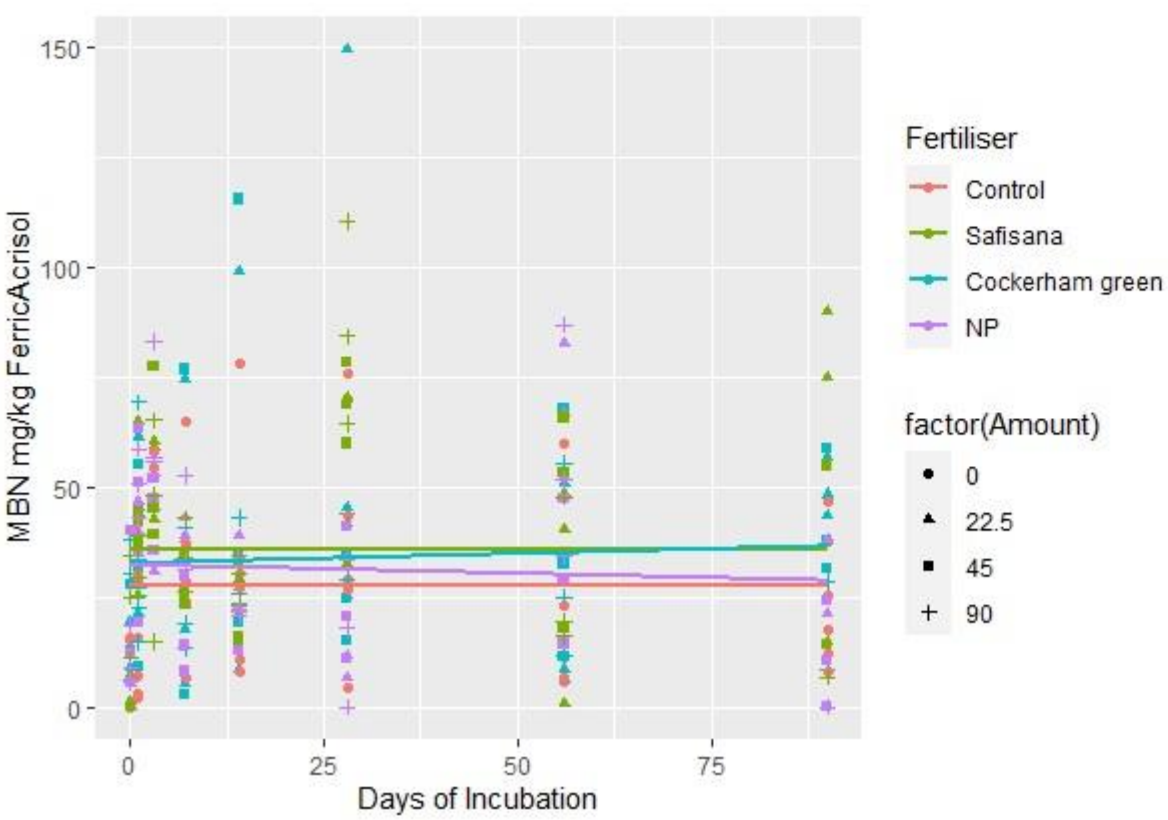

Figure S41- Loess trend on MBN versus Days of Incubation in Ferric Acrisol

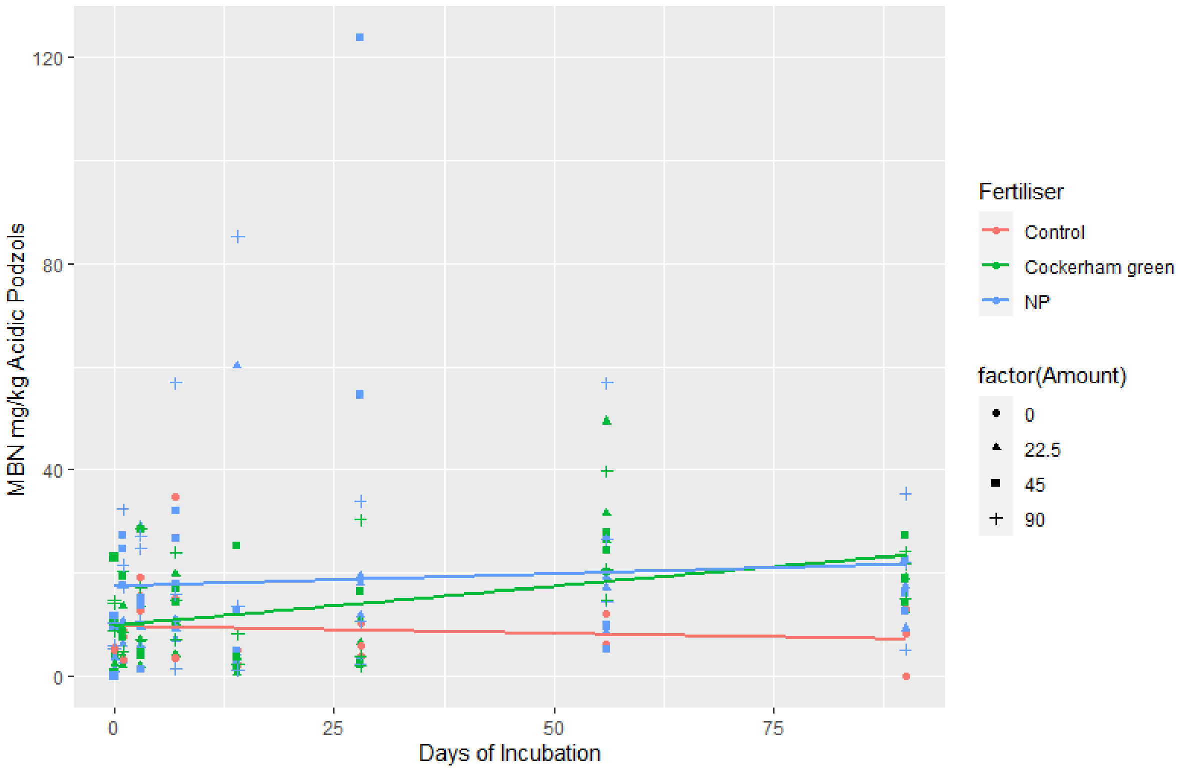

Figure S41- Loess trend on MBN versus Days of Incubation in Sandy Podzols

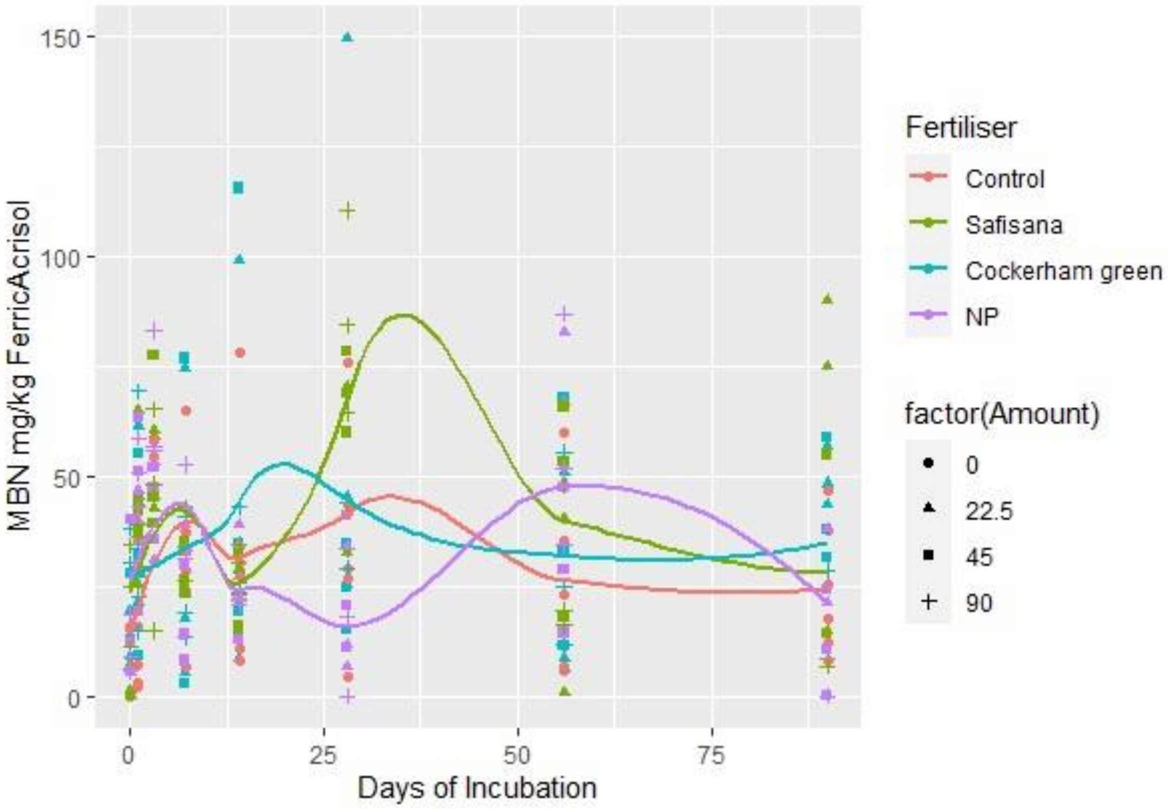

Figure S43- Curve fitting using Loess trend on MBN versus Days of Incubation in Ferric Acrisol

Table S41: Linear relationship between Amount of MBND in Ferric Acrisol soil and time

	Ferric Acrisol	Estimate	Std Error	P-value	Adjusted R Squared	Residual Standard Error	Multiple R squared
Ferric Acrisol	β_0 for Control	27.498523	3.939193	9.74e-09 ***	-0.02173	21.15	1.089e-05
	B for control	0.002251	0.100580	0.982			
	β_0 for Safisana	35.807153	3.772357	3.33e-14 ***	-0.01428	24.73	6.913e-06
	β_1 for Safisana	0.002118	0.096305	0.983			
	β_0 CG	32.62495	3.98638	8.37e-12 ***		26.3	
	β_1 CG	0.04364	0.10180	0.669			
	β_0 NP	32.28949	3.48610	8.75e-14 ***	-0.01139	22.85	0.00286

	β_1 Fertiliser NP	-0.03988	0.08900	0.655				
	Sandy Podzols	Estimate	Std. Error	Pr(>|t|)	Adjusted R-squared	Residual standard error	Multiple R squared	
Sandy Podzols	β_0 Control	27.498523	3.939193	9.74e-09 ***	-0.02173	1.089e-05	-0.02173	
	β_1 Control	0.002251	0.100580	0.982			21.15	
	β_0 CG							32.62495
	β_1 CG	0.04364	0.10180	0.669				
	β_0 NP							17.38070
	β_1 NP	0.04786	0.07861	0.545				

4.5.2 Correlation analysis between MPB and Olsen P

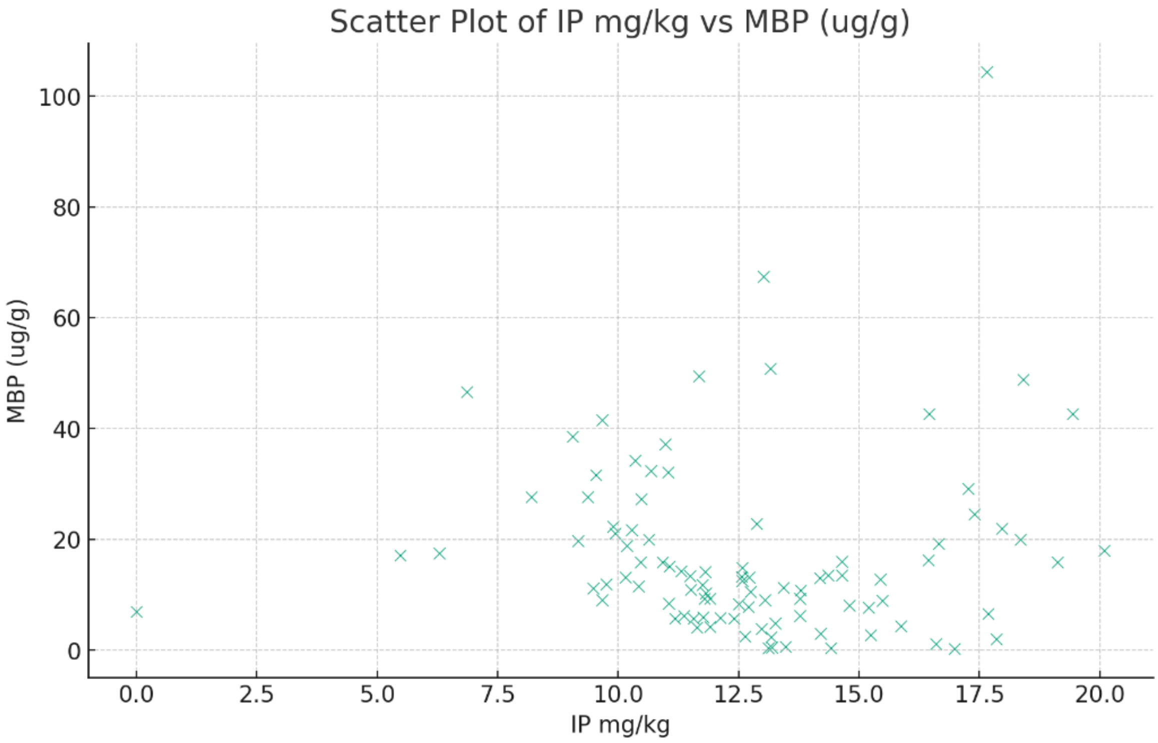

Figure 4.9 Relationship between IP and MBP applied at 90 kg N per ha.

The scatter plot (Figure 4.9) presents the relationship between the concentrations of inorganic phosphorus (IP, measured in mg/kg) and microbial biomass phosphorus (MBP, measured in µg/g) in various samples. IP concentrations range from 0 to approximately 20 mg/kg, while MBP values vary from near 0 to about 100 µg/g. Most of the data points are concentrated within 5 to 15 mg/kg of IP and 10 to 40 µg/g of MBP. There appears to be a positive correlation between IP and MBP. As IP concentrations increase, MBP concentrations also tend to increase, suggesting that higher availability of IP may enhance MBP in these samples.

The data shows substantial variability in MBP concentrations at given levels of IP, particularly in the mid-range. For example, at approximately 10 mg/kg of IP, MBP varies significantly, ranging from about 10 to over 40 µg/g. Some outliers are observed, particularly at higher IP concentrations where MBP values are significantly elevated. These points could be influenced by specific environmental conditions or biological factors not uniformly present across all samples.

The observed positive correlation between IP and MBP suggests that inorganic P may be a limiting nutrient for microbial growth in these environments. The availability of inorganic phosphorus likely supports microbial activity, leading to higher concentrations of microbial biomass P. The notable spread and variability in MBP values across similar IP levels may indicate the influence of other environmental or biological factors, such as pH, temperature, or the presence of other nutrients, which might also affect microbial growth and biomass accumulation. The presence of outliers highlights the complexity of microbial responses to P availability. These outliers may represent unique environmental microsites or conditions where microbial communities are particularly efficient at P uptake or where other growth-limiting factors are mitigated. This analysis underscores the importance of inorganic P in supporting microbial life and suggests a strong link between phosphorus availability and microbial biomass in the sampled environments. Understanding these relationships is crucial for ecological studies and can inform environmental management practices aimed at sustaining microbial biodiversity and function.

5 Evaluating the Response of Micro-Tom Tomatoes to Digestate and Mineral Fertilisers under Diverse Watering Conditions

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Abstract

Continuous cropping, without supplemental fertilisation, has depleted many agricultural systems, leaving them with diminished soil carbon and nutrient stocks. In response, this study evaluated the efficacy of anaerobic digestate (AD), a nitrogen and organic matter-rich material derived from waste management processes and compared it with conventional mineral fertilisers (nitrogen and phosphorus). The AD sources included Safisana from Ghana and Cockerham Green from Lancaster, UK. Both AD and mineral fertilisers were applied at respective rates of 90 kg N/ha and 90 kg N/ha plus 45 kg P/ha to pots containing nutrient-deficient sandy podzol with a pH of 6.5, low nitrogen, and carbon levels. Tomato plants (Solanum Lycopersicon cv. Micro-Tom) were cultivated over a period of 70 days (10 weeks). The primary aim was to investigate the effects of these fertilisers on plant growth and productivity under different water application regimes, 80% and 120% water holding capacity (WHC), based on a WHC of 0.28 ± 0.02 g/g H_2O on a dry basis. Secondary objectives included assessing nutrient retention and leachate dynamics following fertilisation and their impact on plant productivity. The results revealed no significant differences ($p > 0.05$) in plant growth or productivity between the AD and mineral fertiliser treatments, nor were effects observed from varying the water application regimes. These findings suggest a limited response to nitrogen or a balance of nutrient supply within the tested period. The study highlights the complex interplay between fertiliser type, water management, and soil nutrient dynamics, emphasising the need for integrated soil and water management strategies to enhance the sustainability of agricultural practices. Hypothesis testing focused on the differential effects of the irrigation regimes post-fertiliser application revealed no statistically significant impact on the yield outcomes, indicating that neither increasing

nor decreasing the standard water supply altered the effectiveness of the applied fertilisers within the experimental timeframe.

5.1 Introduction

Continuous agriculture has rendered many agricultural lands infertile, especially in Sub-Saharan Africa (SSA). According to Stewart et al. (2020), there are low crop yields due to loss of soil fertility, improper land use, soil erosion, nutrient leaching due to high incidence of rainfall, and the non-replacement of nutrients removed by cropping and harvesting. Salgado et al. (2022) note that because low yields threaten food security, there is a need to produce more food to cope with an increasing population, as a larger population leads to increased demand for food (Tetteh et al., 2017).

The Abuja summit on fertiliser declared that SSA can only increase food production and alleviate poverty with increased fertiliser use (Ntinyari et al., 2022). Meanwhile, Chartzoulakisa and Bertaki (2015) emphasized the critical role of integrating water management with nutrient application, as foundational to enhancing agricultural productivity. This relationship is mechanistically vital because adequate moisture not only facilitates nutrient solubility and mobility but also supports robust root growth, necessary for efficient nutrient uptake. Furthermore, optimal soil moisture levels are crucial for microbial activity and nutrient transformations, processes that are integral to maintaining soil fertility (Borowik, & Wyszkowska, 2016) This is especially pertinent in SSA, where variable agroecological conditions and socio-economic factors present unique challenges and opportunities for implementing sustainable farming practices

(Rege and Sones, 2022). In regions where water scarcity and nutrient-poor soils often constrain agricultural output, the deployment of efficient irrigation techniques coupled with effective fertilisation strategies is paramount for enhancing crop yield and ensuring food security (Moyo, 2016). To ensure this, organic sources of fertiliser, such as digestate from anaerobic digestion, may be utilised.

Anaerobic digestion, which transforms biomass into biogas and bio-digestate in a microorganism-rich environment (Ghandi et al., 2022), offers a way to increase crop yields, sequester soil carbon, and improve fruit quality (Alburquerque, 2012; Nkoa, 2013). Research suggests digestate could be an effective alternative to mineral fertilisers, provided its application is tailored to meet the specific nutrient requirements of crops and account for environmental factors, including optimal irrigation practices (Tampio et al., 2022). Haraldsen et al. (2011) demonstrated that digestate can be a viable alternative to inorganic fertiliser when applied with equivalent N levels, as it resulted in comparable barley production and nutrient uptake rates. Walsh et al. (2012) similarly found that grass yields in controlled experiments using liquid digestate, mineral fertilisers, and other organic fertilisers were comparable, attributing this to the diverse nutrient composition present in digestate.

In examining the agronomic benefits of organic soil amendments Svenson et al. (2004) compared the land application of compost and digestate, both derived from source-separated domestic wastes. They concluded that while composts required additional N supplementation, digestate needed P supplementation to maintain grain quality and yields. Furthermore, studies evaluating the impact of digestate on the yields of various crops, such as lettuce, watermelons, cauliflower, tomatoes, and peppers, consistently showed positive influences from digestate addition, with yields either surpassing or being at par with those from mineral fertilisers (Zhou et al., 2007; Lu et al., 2008; Liu et al., 2009; Montemurro, 2010; Alburquerque et al., 2012).

This study seeks to examine the comparative effectiveness of various digestate sources as fertilisers against traditional mineral fertilisation, specifically analysing their impact on the micro-Tom tomato cultivar under two distinct water application regimes in a controlled glasshouse environment. Importantly, this research integrates considerations of irrigation efficiency, focusing on the variations of irrigation based on soil water holding capacity (WHC) to ensure precise water delivery for micro-Tom tomato productivity. By optimising water application rates based on the soil's moisture retention capabilities, we aim to prevent nutrient leaching and improve water use efficiency, thereby supporting sustainable water and fertiliser management practices in SSA agriculture.

In determining the appropriate fertiliser dosage, this study draws inspiration from Essel et al. (2020), who investigated the nutrient response dynamics of maize to mineral fertilisers. Their findings indicated that an optimal nitrogen application of 60 kg N/ha resulted in the highest maize yield of 5 tons/ha, with a noted decrease in yield at higher application rates. Motivated by these insights, we hypothesise that increasing the application of digestate nitrogen to 90 kg N/ha could lead to higher or equivalent tomato yields compared to conventional urea phosphorus (NP) applications. This hypothesis is rooted in the understanding that adjusting fertiliser application rates, in performance with tailored water management practices, can significantly influence crop production outcomes, potentially offering a path towards enhanced agricultural productivity and soil health in SSA.

5.2 Materials and methods

5.2.1 Soil source and collection

Topsoil samples were collected from the England Forestry Commission, Abbots Moss Nursery Delaware in Cheshire, UK and transported to Lancaster. The soils were classified as sandy Podzols with pH 6.5. Prior to using the experimental soil, *Ferric Acrisol* was obtained from Ghana, West Africa and characterised. The sandy Podzols were sourced to mimic the characteristics of *Ferric Acrisol. Ferric Acrisol* is a sandy loam derived from weathered tertiary sands and is among the dominantly cultivated soils in the part of the semi-arid tropics in Ghana. Morphologically the soil is well drained, and colour varies from red to brown. The soils have moderate acidity of pH 5.0 – 6.0. Information on *Ferric Acrisol* obtained was used in sourcing the experiment soil. The soil samples were air-dried, sieved through a 2-mm screen, and stored at 4°C temperature until use. The soil particle size distribution was determined using laser diffractometer (Coulter Beckman LS13320). Briefly 5-gram soil samples were soaked in 5 -10 ml hydrogen peroxide for 24 hours to remove organic matter. The soil sample was dispersed in a liquid medium to separate individual particles. The dispersed soil sample was introduced into the laser diffractometer instrument. The laser beam passes through the sample, and the scattered light is collected at various angles. The instrument detects and analyse the diffraction patterns to determine the particle size distribution based on the measured diffraction patterns (Allen, 1990). Measurements were done in triplicates. The particle size distribution was 80 % sand and 20 % silt hence soils were classified as sandy soil. Soil WHC was also determined to be 28 ± 2 % dry weight (The experimental soil samples (Podzols) had similar texture when compared with the *Ferric Acrisol* hence used for the experiment as a synthetic Ghana soil presented in Table 5.1.

Table 5.1 Characteristics of the Ferric Acrisol and Sandy Podzols soils

Parameter (fresh basis)	**Acronym**	**Units**	**Ferric Acrisol**	**Sandy Podzols**	P-Value
Organic (Volatile) Matter	OM	%	4.79 ± 0.1	2.24 ±0.1	<0.001
pH	pH	-	5.8 ± 0.1	6.5 ±0.1	<0.001
Electrical Conductivity	EC	mS/m	25.7±2.1	51.33 ± 1.3	<0.001
Total N	TN	%	0.3 ± 0.1	0.08 ±0.1	0.00934
Total carbon	TC	%	1.2 ± 01	1.3 ±0.1	0.10124
Carbon: N ratio	C: N	-	4 ± 0.1	16 ±0.1	<0.001
Total Phosphorus	TP	%	0.027± 0.01	0.014 ±0.1	0.90509
Particle size analysis	Clay	%	7.7 ± 0.1	0.6 ±0.1	<0.001
	Silt	%	4.7 ± 0.1	2.5 ±0.1	<0.001
	Sand	%	87.6 ±0.1	97.0 ±0.1	<0.001

5.2.2 Digestate source and characterisation

The digestate used in this study was sourced from Ghana and the UK. The two digestate samples utilised were Safisana (from Ghana) and Cockerham Green (from the UK, in the Lancashire area). The Safisana digestate originates from municipal waste, while Cockerham Green energy digestate comes from agricultural waste. The digestate samples were analysed for pH, electrical conductivity (EC), total solids (TS), organic matter (OM), total N (TN), available N (NH_4^+-N and NO_3^--N), and elemental composition (C and N). The pH and EC of the samples were measured using a 1:5 ratio (i.e., one part of digestate to five parts of ultrapure milli-Q water). The measurements of pH and EC were conducted with a Mettler Toledo® Seven Compact™ S220 pH/Ion meter and a Jenway® 4510 bench conductivity/total dissolved solids meter, respectively. Briefly, a 5 g sample was mixed with 25 ml (1:5) of water, followed by a pH meter reading. Total solids (TS) and volatile solids (VS) were determined using standard methods (APHA, 2012). Extractable NH_4^+-N and NO_3^--N were determined for both the digestate and urea. NH_4^+-N and NO_3^--N were extracted from the samples using a 2M KCl solution and quantified using an auto analyser (AA3, SEAL Analytical; Method No G-102-93 Rev. Multitest MT7/MT8). Subsamples of the digestates were sent to NRM Laboratories, UK, where the TN of the digestate samples was determined. The characteristics of the digestates are presented in Table 5.1. All chemical analyses were performed in triplicate.

Table 5.2 Nutrient composition of Fertilising material (Digestate and Urea)

Parameter	**Acronym**	**Units (fresh basis)**	**Safisana**	**Cockerham Green**	**NP (Urea-Tripple superphosphate)**
Dry Matter	DM	%	68.9 ± 2	7.8 ± 2	-
pH	pH	-	5.8± 0.2	8.3 ± 0.5	8.0 ± 0.1
Electrical Conductivity	EC	mS/m	305 ± 5	749 ± 3	-
Total N	TN	g/kg	23.5 ± 1.0	6.2 ± 0.2	460
Mass of Digestate / Fertiliser	MD	g/kg of soil	0.41 ± 0.1	1.58 ± 0.1	0.02
Total Carbon	TC	g/kg	146 ± 1.2	263 ± 0.68	-
Total Phosphorus	TP	g/kg	14.0 ± 1.0	1.2 ± 0.4	480
Total Potassium	TK	g/kg	6.3 ± 0.1	3.9 ± 0.3	-

5.2.3 Experimental set-up

The experiment was conducted using pots (11 cm in diameter and 20 cm in depth) with a flexible mesh (0.5 mm pore size) placed at the bottom of each pot, filled with 700 g of soil (dry weight). The fertilising materials studied (Safisana digestate, Cockerham Green digestate, and Urea-Phosphate (as NP)) were individually mixed with the soils by hand on a mixing tray and placed in the pots at a rate equivalent to 90 kg N ha^{-1}, considering a soil bulk density of 1.2 g/cm^{3} and a plough depth of 20 cm. A control treatment, referred to interchangeably as "Control" or "Unamended Soil," consisting of soil without any amendments, was also included. Soil water content was adjusted to 80% and 120% WHC (100% WHC = 0.28 ± 0.02g /g H_2O dry basis) in all treated soils using distilled water. The pots at 120% WHC, containing amended soil, were watered beyond their WHC to allow for drainage overnight (8-12 hours) into a saucer.

Four leaching events were conducted bi-weekly on days 0, 14, 28, and 56, with the initial leaching event conducted separately from those on days 14, 28, and 56. Leachate samples were collected and analysed for pH, electrical conductivity (EC), and available N (NH_4^+-N and NO_3^--N). The experiment comprised a total of 80 experimental units, calculated as 4 amendment levels × 2 water application levels × 5 replicates × 2 conditions (planted and unplanted soils).

5.2.4 Chemical Analysis

Soil parameters were analysed as follows: Soil pH was determined in an aqueous solution using a 1:5 soil-to-water ratio. Total N (N), ammonium N (NH_4^+-N), and nitrate N (NO_3^--N) were extracted with 1M KCl, and the filtrate was analysed for inorganic N using an auto-analyser (Elementar Vario EL III). The organic matter (OM) content was determined by measuring the weight loss following ignition in a muffle furnace (Carbolite, CWF 1000) at 550°C for 5 hours. Total carbon (C) and N (N) contents were analysed in dried samples using a CN analyser (TruSpec CHN; LECO, Michigan, USA). The samples were sieved to 2mm and air dried, then ground using a ball mill and wrapped into tin cups for analysis. Carbon and N percentages recorded in the analysis were converted to stocks for statistical analyses.

5.2.5 Microbial biomass Carbon and Nitrogen

The extraction of MBC and MBN was performed using the chloroform fumigation method as described by Brookes et al., (1985) and Vance et al., (1987). Duplicate moist soil samples were treated with and without chloroform fumigation following the protocols established by Brookes et al. (1985) and Vance et al. (1987). The samples were extracted in a 1:5 w/v ratio using 0.5 M K_2SO_4 at a pH of approximately 7, and the extracts were filtered through Whatman No. 42 filters after shaking for 30 minutes on a shaker. The filtrate was analysed for extracted C and N using a TOC analyser (Shimadzu TOC-LCPN TN).

5.2.6 Data collection

Growth parameters such as plant height and stem diameter were measured weekly from weeks 2 to 6. Plant height was measured using a tape measure, while stem diameter was measured using a digital vernier calliper. The number of leaflets and leaf area were determined at the end of the experiment. The number of leaflets was counted during the measurement of leaf area, with each leaflet being recorded sequentially. Leaf area was measured using a digital area meter (Model 3100, Li-Cor, NE, USA) at the conclusion of the experiment. Above-ground biomass was obtained by cutting the plant stem just above the soil surface in the pots using scissors. The cut above-ground biomass was then stored in sample paper bags and dried at a temperature of 60 ^{o}C in a drying cabinet until constant weight was achieved. Dried samples were further milled and analysed.

5.2.7 Methods for measurements

5.2.7.1 Chlorophyll content

The relative chlorophyll content in selected leaves was measured weekly using a chlorophyll meter. For each plant, the relative chlorophyll content of four to six leaves was assessed. Chlorophyll meters, such as the SPAD-502, estimate chlorophyll content non-destructively by measuring the absorbance of light at specific wavelengths. These measurements provide an index of chlorophyll concentration that correlates with the actual chlorophyll content, allowing for rapid assessments of photosynthetic activity and plant health without harming the plant (Maxwell and Johnson, 2000).

5.2.7.2 Chlorophyll a fluorescence assay

Chlorophyll fluorescence assay was measured using a Handy Plant Efficiency Analyser (Handy PEA, Hansatech Instruments, Norfolk, UK) (Chen et al., 2022). Briefly, leaves were adapted to the dark condition for 30 minutes before measuring chlorophyll a fluorescence in each treatment group. The Maximum Quantum Efficiency of PSII (Fv/Fm) was calculated by dividing Fv by Fm. This ratio indicates the efficiency with which PSII can convert absorbed light into chemical energy. A healthy, well-functioning plant typically has an Fv/Fm ratio of around 0.8 to 0.85. Plant Photosynthetic Electron Transport Activity (PEA) can be measured using various techniques, with chlorophyll fluorescence (Jia et al., 2021b).

5.2.8 Water Application

Plants received consistent irrigation to maintain optimal moisture levels Throughout the experiment. The baseline water application was set to maintain 80% WHC, corresponding to 144 ml of water per day. This rate was calculated to offset the water loss due to evapotranspiration, ensuring that each plant received sufficient water daily to replace what was lost. During leaching events, irrigation was increased to 120% (corresponding to 212.7 ml) of the baseline WHC to simulate excess water conditions, while maintaining the regular watering schedule on other days.

5.2.9 Post Planting analysis

Plant biomass collected from the pots was weighed to determine its fresh weight (FW) and then oven-dried at 55°C for 120 hours to ascertain the dry weight (DW) content. The dried samples were subsequently ball milled to pass through a 1 mm sieve (Retsch SM-2000, Germany). Carbon (C) and N content were determined using an elemental analyser.

5.2.10 Statistical Analysis

A two-way Analysis of Variance (ANOVA) was employed to assess the significance of the effects that different treatments had on plant growth and yield parameters. Each treatment was replicated five times, with these replicates serving as blocks in the analysis. To determine significant differences between treatment means, a Tukey post-hoc test was conducted at a 95% confidence interval ($p<0.05$). All statistical analyses were performed using R software, ensuring that the significance threshold was consistently set at 0.05.

5.3 Results and Discussion

5.3.1 Effect of Water application on N Availability

Figure 5.1 presents the comparative analysis of NH_4^+-N and NO_3^--N levels, expressed in milligrams per kilogram, as observed at the outset (Initial) and conclusion (Irrigation 80 and 120) of the growth cycle.

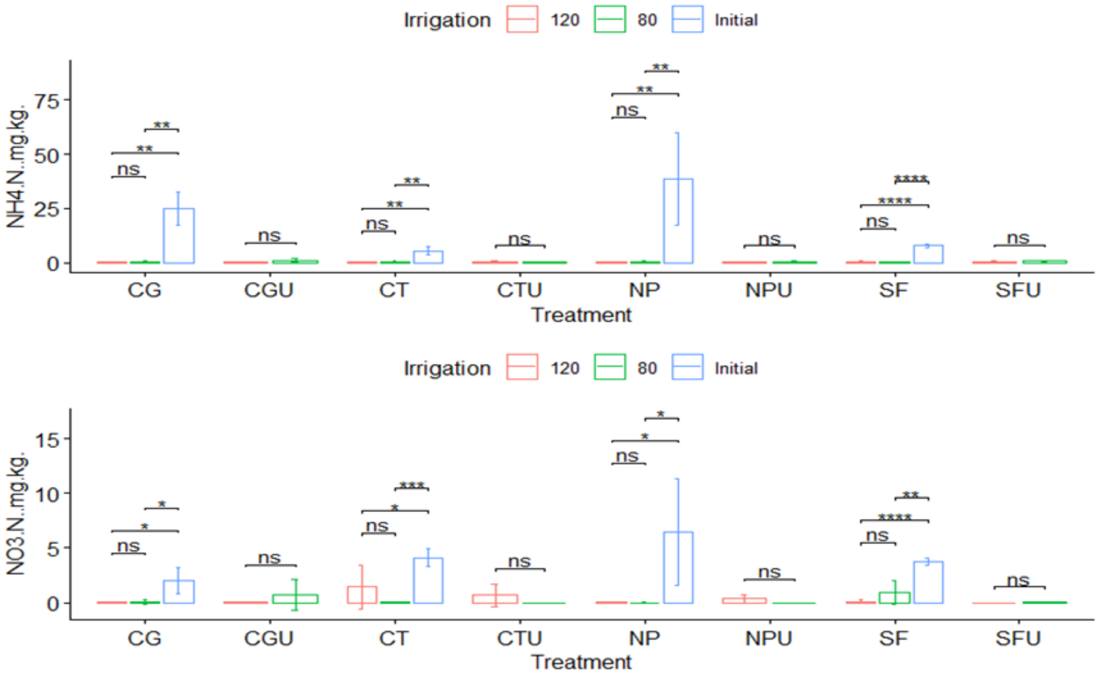

Figure 5.1 Effect of treatment and water application on N availability on Initial and final days (Note: Values are mean of 5 replicates + SD; notations * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$)

These assessments were conducted across diverse soil treatments using various fertilisers, under two distinct irrigation scenarios. The treatment categories include Cockerham Green (CG) alongside its unplanted control (CGU), Safisana (SF) contrasted with unplanted Safisana soil (SFU), NP fertiliser (NP) in comparison with unplanted NP (NPU), and untreated soil (CT) against its unplanted equivalent (CTU).

5.3.2 Ammonium N (NH_4^+-N) Concentration

In general, there were no significant differences ($p > 0.05$) between the 80 and 120 % WHC for all treatments in planted and unplanted conditions (Figure 5.1). However, when the initial amount of NH_4^+-N was compared with the planted conditions there were significant differences ($p < 0.05$). Suggesting that both planted and unplanted conditions exhibit similar NH_4^+-N dynamic in the experiment. The NH_4^+-N concentrations did not exhibit a uniform response across treatments.

5.3.3 Nitrate N (NO_3^--N) Concentration

Regarding NO_3^--N concentrations (Figure 5.1 Effect of treatment and water application on N availability on Initial and final days (Note: Values are mean of 5 replicates + SD; notations * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$), CG treatments exhibited a significant reduction ($p<0.05$) at 80 % WHC irrigation compared to the initial condition ($p<0.05$), indicated by a single asterisk (*). This suggests that the irrigation level could be affecting nitrate leaching or plant uptake patterns. The SF treatment displayed a complex response, with a highly significant ($p<0.05$) decrease in NO_3^--N concentration at 80 % WHC ($p<0.05$) and a highly significant increase ($p<0.05$) at 120% WHC compared to 80% WHC irrigation ($p<0.05$), suggesting differential effects of irrigation on nitrate availability and dynamics in the soil. For NP treatments, a significant ($p<0.05$) reduction in NO_3^--N concentration at the 80 % WHC irrigation level compared to the initial condition was observed (*), while no significant ($p>0.05$) change was noted at the 120% WHC level. This pattern may imply that the NP fertiliser's influence on NO_3^--N is more pronounced at lower irrigation levels.

These results suggest that the response of soil N species to irrigation is influenced by the interplay between soil treatment (fertilising material application) and the presence of plants. While planted treatments with 120% WHC irrigation (CG, NP, CT) consistently showed increased NH_4^+-N concentrations, potentially due to higher nutrient uptake by plants or increased microbial activity, the NO_3^--N concentrations did not follow a consistent pattern. This variability in NO_3^--N response could be due to a combination of factors, including plant uptake efficiency, nitrification rates, and the potential for leaching under varied irrigation conditions.

Water application and management plays a major role in N dynamics, which are crucial for plant growth and the health of soil ecosystems (Sun et al., 2024). Excessive water application can lead to the leaching of N and its compounds away from crop roots and out of the soil (Wang & Li, 2019). N exists in various forms, including ammonium (NH_4^+) and nitrate (NO_3^-), which can be easily leached from the soil through excess water, making them less accessible to plant roots. Even if N is available, excessive water application can dilute the concentration of the ions (NH_4^+ and NO_3^-) hence decreasing the availability of N and making it less accessible for plant uptake. The overall effect leads to nutrient deficiencies, thus reducing crop yields. Other negative effects of excessive water application include prolonged plant stress due to waterlogging and a reduction in oxygen in the root zone of plants. This impacts negatively on microbial activity responsible for the N transformation process, thus hindering the conversion of nitrate (NO_3^-) to gaseous forms like nitrous oxide (N_2O) or N_2 through denitrification.

5.3.4 The Effect of Water Application and Fertilising Materials on Leaf Chlorophyll Content

Figure 5.2 presents the chlorophyll content measured in micrograms per square meter (µg/m²) for treatments (fertilising materials addition and water application) over a span of 10 weeks (Day 21 to Day 70), categorised by two different irrigation levels namely 80% WHC and 120% WHC of different treatment of fertilising material. The chlorophyll content ranged from 63 to approximately 500 µg/m².

For the 80% irrigation level, there is an observable general decline in chlorophyll content over time across most treatments. In contrast, at the 120% irrigation level, the chlorophyll content maintains relative stability across the weeks for each treatment, despite some variances. At both irrigation levels, the treatments Cockerham Green and NP generally exhibit higher chlorophyll content compared to Safisana and Unamended soil, with this difference being particularly pronounced in the initial weeks. The trend of chlorophyll content for all treatments tends to show a decline as the weeks advance, which is especially marked in the final week (Day 70). No significant differences ($p<0.05$) were observed between the treatments for Days 21, 28, 35, 42, and 70. However, significant differences ($p<0.05$) were found on Day 56 for the Safisana treatment (t-stat = 2.460; p-value = 0.039) and on Day 63 for both the Safisana (t-stat = 2.993; p-value = 0.017) and Unamended Soil treatments (t-stat = -3.155; p-value = 0.016) when comparing the 80% and 120% irrigation levels.

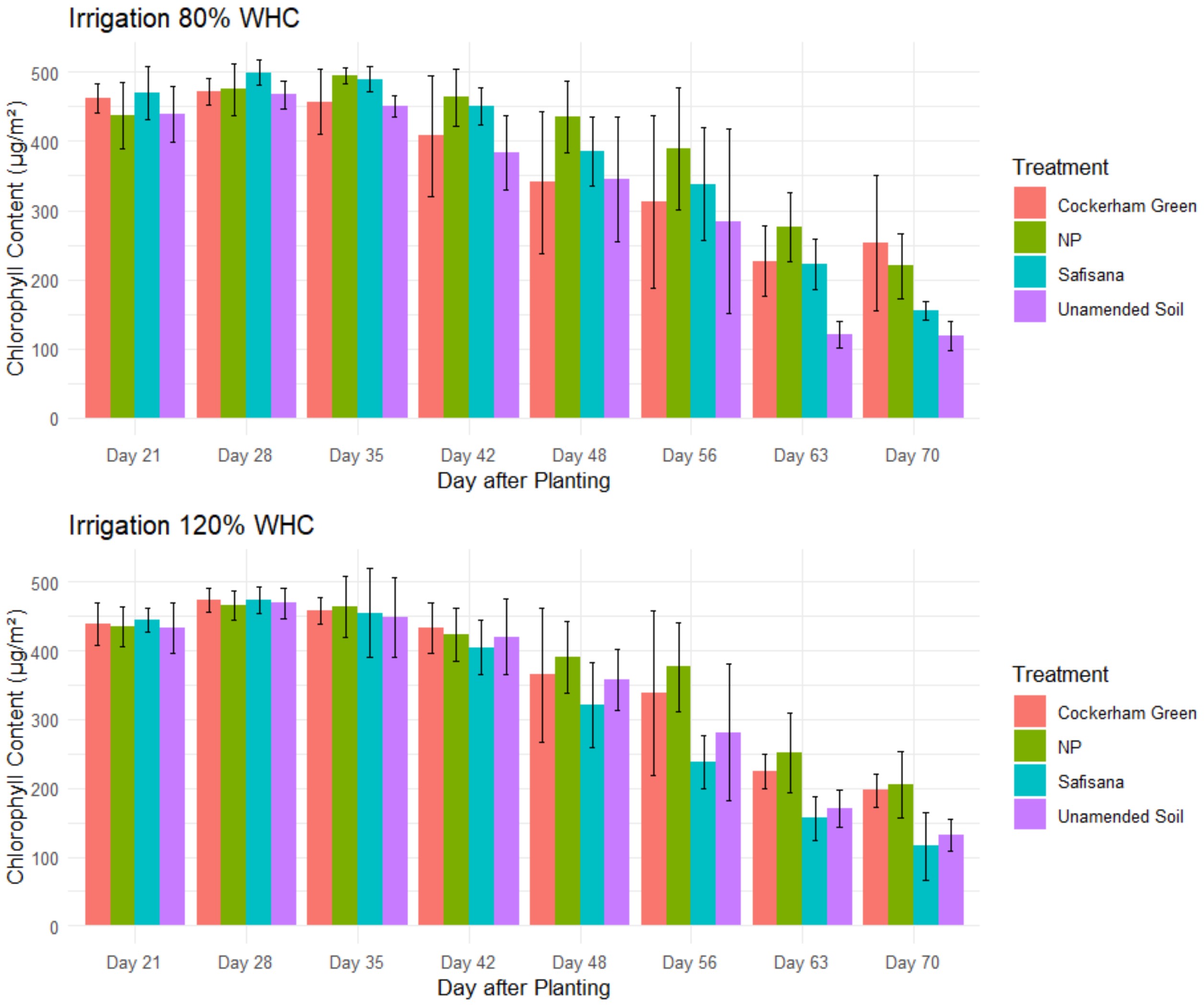

Figure 5.2 Chlorophyll Content Variation Across Different Treatments and Irrigation Levels (Note: Values are mean of 5 replicates + SD)

N is a critical component of the chloroplast, playing a vital role in chlorophyll biosynthesis and photosynthesis (Huang et al., 2021). It is estimated that approximately 75% of N is allocated to the chloroplast, leading to increased chlorophyll content with higher N levels (Li et al., 2013; Sun et al., 2016; Huang et al., 2021) as shown by the higher chlorophyll content recorded in the initial days after planting suggesting that N in fertilising material and soil (for the unamended soil) affected the chlorophyll content. Initial weeks show a positive effect on chlorophyll content, which declines in the later weeks, likely due to a reduction in soil N levels. Raab and Terry (1994) proposed that the observed increase in chlorophyll content under nitrogen treatment may be attributed to changes in chloroplast morphology. Specifically, Raab and Terry (1994) suggest that nitrogen availability can lead to an increase in chloroplast size and modify the configuration of the chloroplast's basal grains, which are essential components of the chloroplast structure involved in photosynthesis. These morphological changes may enhance the chloroplast's ability to capture light and, consequently, increase chlorophyll production. Both water management and fertilisation practices significantly affect leaf chlorophyll content (Li et al., 2018). Optimising water and fertiliser applications is crucial for influencing leaf chlorophyll content, a key indicator of a plant's photosynthetic efficiency and overall health (Li et al., 2018). Water availability is essential for chlorophyll production and maintenance as seen in both irrigation 80% and 120% WHC suggesting that there was enough water availability for chlorophyll production and maintenance. Although this was not observed in our experiment water-stressed plants close their stomata to conserve water, which limits CO_2 uptake necessary for photosynthesis (Li et al., 2018). This reduced photosynthesis can lead to chlorophyll depletion. Conversely, overirrigation negatively affects leaf chlorophyll content. Excessively wet conditions can reduce oxygen availability to plant roots, promote root diseases, and hinder nutrient uptake, potentially leading to a decrease in chlorophyll content.

5.3.5 Effect of water application and fertilising materials on the plant Intrinsic photosystem II (PSII) efficiency (estimated from the ratio of variable over maximal chlorophyll fluorescence, Fv/Fm)

Chlorophyll fluorescence measurements offer a valuable window into plant health, stress responses, and photosynthetic efficiency, providing insights into plant photosynthetic performance in response to light energy and electron transport efficiency (Chen et al., 2022). Understanding these dynamics of chlorophyll fluorescence and photosynthetic efficiency contents helps researchers optimise crop growth and environmental sustainability (Guo et al., 2006; Kalaji et al., 2018).

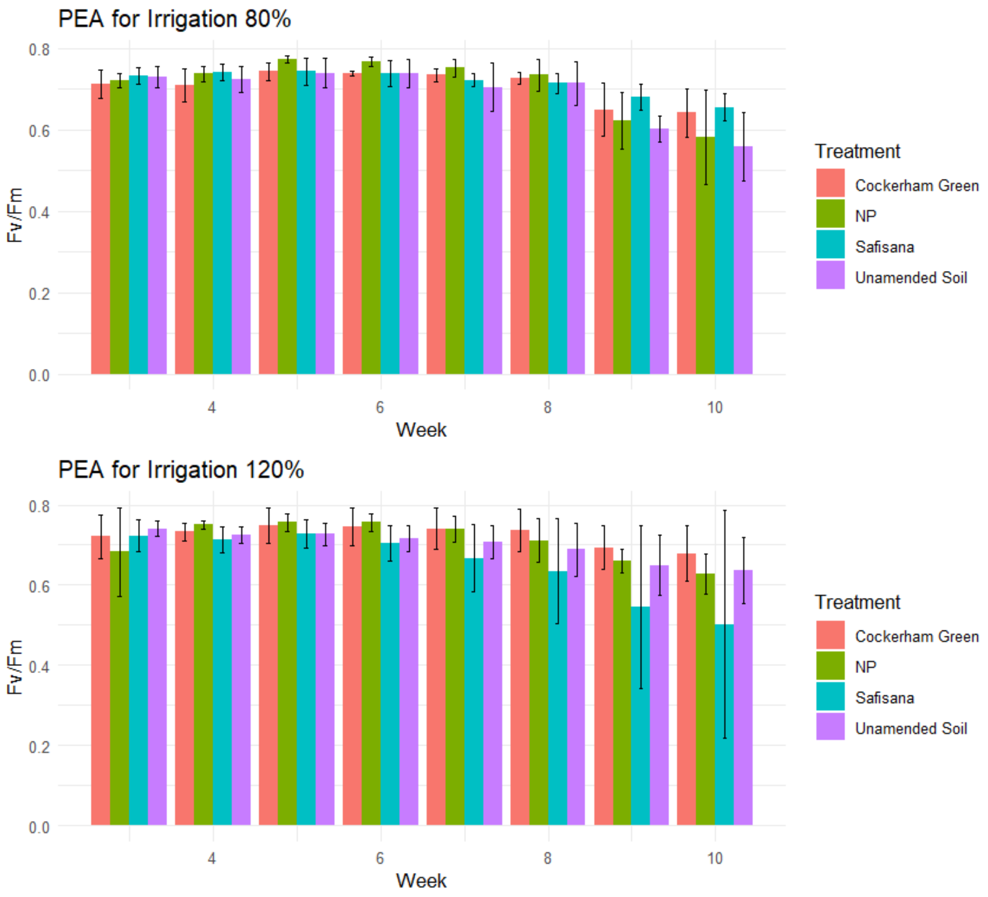

Figure 5.3 Effects of treatment and irrigation resulted in a decreasing Fv/Fm (Note: Values are mean of five replicates + SD)

The investigation into the effects of water application and fertilising materials on plant Fv/Fm revealed significant insights into the adaptive strategies of plants under varying environmental conditions. Typical values for healthy, unstressed plants are around 0.83. At 80% irrigation, a consistent Fv/Fm was observed across all treatments, with values alternating slightly but remaining within the 0.6 to 0.7 range. The presence of fertilising materials in soil did not show a pronounced effect on Fv/Fm, suggesting a resilience or an optimal water use efficiency under moderate water stress conditions. Conversely, at 120% irrigation, indicative of surplus water conditions, Fv/Fm measurements were similarly stable across all treatments and comparable to those under 80% irrigation. This suggests that the excess water did not present any additional benefit to Fv/Fm, possibly due to a saturation point beyond which additional water does not enhance photosynthetic efficiency.

The data suggests that under both irrigation regimes, the plants adjusted their physiological mechanisms to maintain a relatively stable Fv/Fm (Bacelar, 2007). This stability across treatments and irrigation levels may imply an intrinsic plant tolerance to a certain range of water variability, especially in the context of the fertilising materials used. It is noteworthy that none of the soil amendments provided a distinct advantage over the Unamended Soil in terms of Fv/Fm, suggesting that the soil's intrinsic fertility or the plants' nutrient-use efficiency was sufficient to sustain near-optimal photosynthetic activity. There is also the possibility that the soil treatments had effects on other aspects of plant growth and health not captured by intrinsic PSII efficiency (Fv/Fm) measurements alone. For instance, although Fv/Fm did not vary greatly with different fertilising materials, these materials could have influenced root development, nutrient uptake, or stress resistance, which would merit further study.

Given the lack of intrinsic PSII efficiency (Fv/Fm) enhancement at higher irrigation levels, our results corroborate the hypothesis that there is an optimal water range for photosynthetic activity, beyond which additional resources do not translate into increased electron transport efficiency. This finding is critical for water resource management, particularly in the context of ensuring agricultural sustainability in the face of varying water availability.

The study underscores the necessity of integrating Fv/Fm measurements with other physiological and growth parameters to fully understand the impact of fertilising materials and water application on plant performance. It also opens avenues for further research into the thresholds of water and nutrient availability that optimise photosynthetic efficiency and plant yield, especially in an era where water conservation is becoming increasingly important.

5.3.6 Effect of Water Application and fertilising material on Above-Ground Biomass, Leaf Area, Number of Leaves, and Dry Fruit Weight

The dry fruit weight of tomatoes, as well as the total above-ground biomass, leaf area, and number of leaves, were not significantly ($p<0.05$) affected by the amount of irrigation or the type of fertilising material applied. This includes specific findings that applying water at 80% water holding capacity (WHC) did not impact these growth parameters, as shown in Figure 5.

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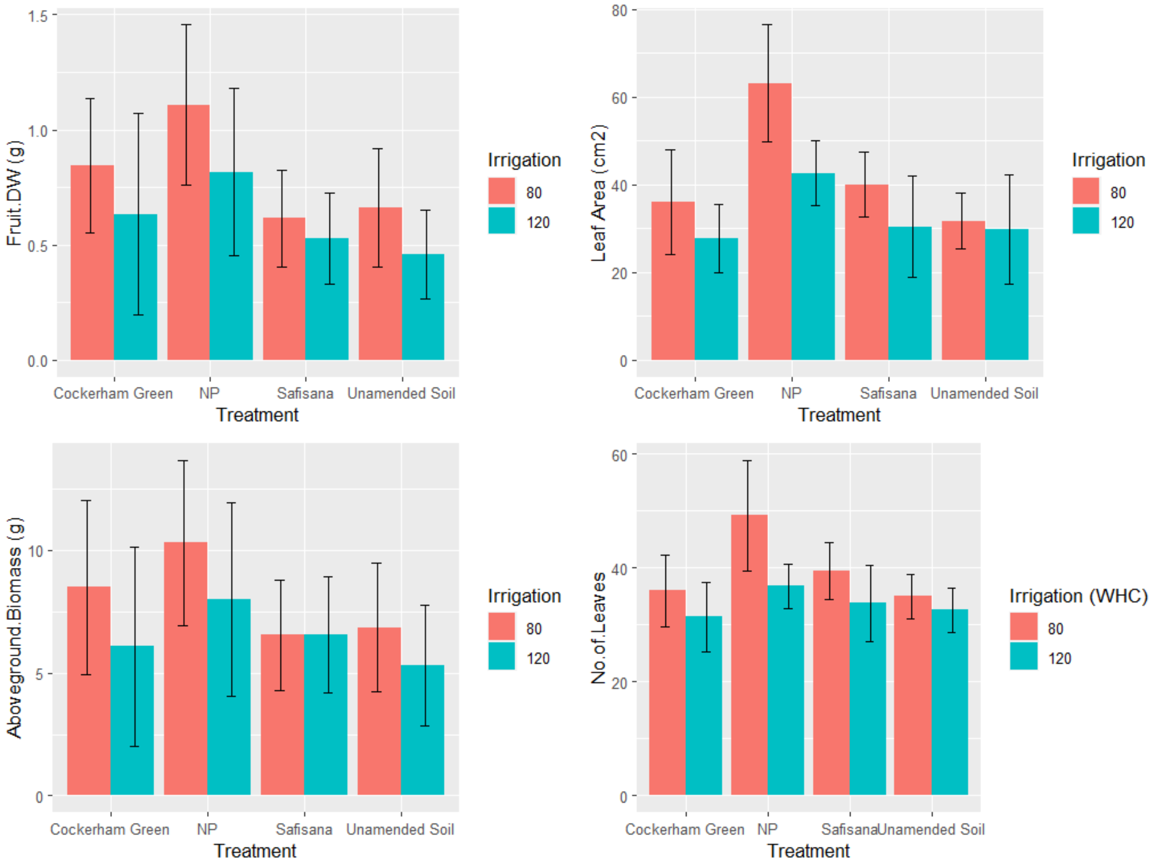

Figure 5.4a Effect of water application aboveground biomass top left, fruit biomass (Fruit DW) top right, Leaf Area bottom left and No of Leaves bottom right (Note: Values are mean of 5 replicates + SD)

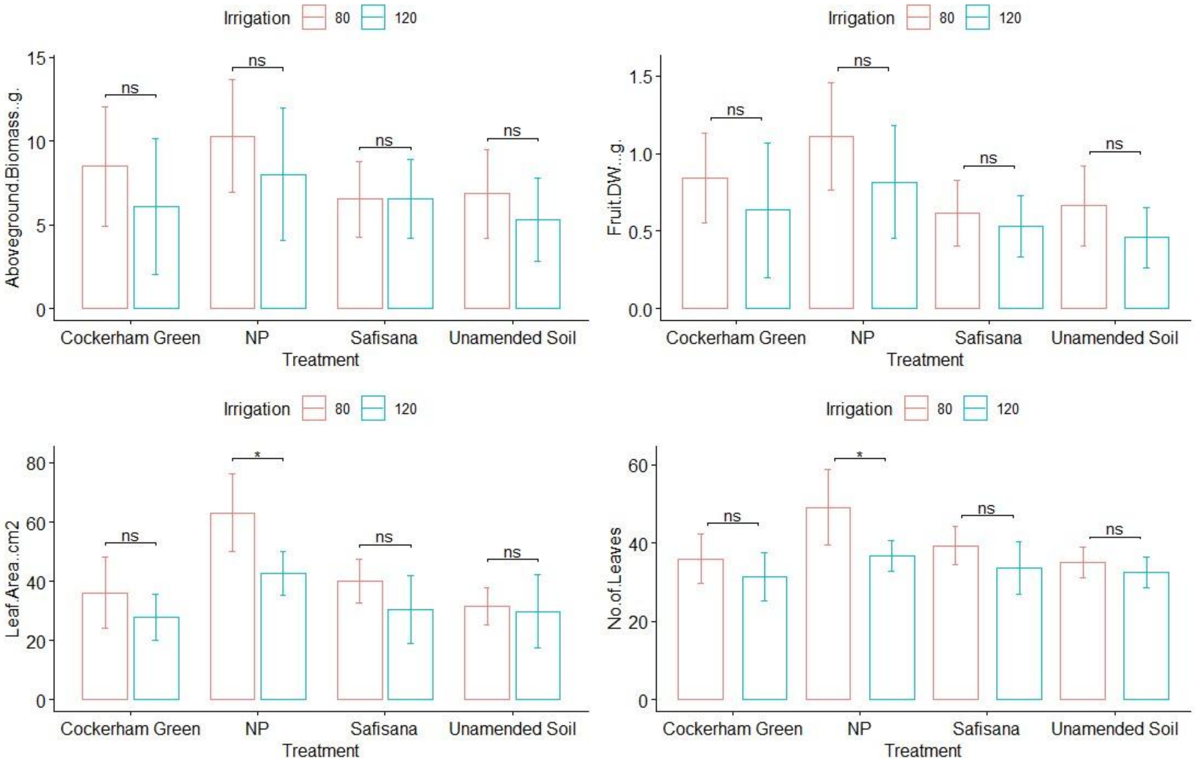

Figure 5.4b Effect of water application aboveground biomass top left, fruit biomass (Fruit DW) top right, Leaf Area bottom left and No of Leaves bottom right

The lack of significance between the water application rate and fertiliser type on tomato above-ground biomass, leaf area, number of leaves, and fruit weight may be attributed to plant resilience, optimal range of water and nutrient availability, soil properties and water retention, limitations of fertilising materials, experimental design, measurement sensitivity, or genetic factors (Cui et al., *2024;* Ullah et al., 2021). Tomatoes may possess a certain level of resilience to variations in water availability, particularly if the range between 80% and 120% WHC does not represent extreme conditions for these plants (Mukherjee et al, 2023). This resilience enables them to sustain growth and development up to a certain threshold of water stress or excess. Furthermore, the conditions of the experiment might have fallen within the optimal range for tomato growth, where both 80% and 120% WHC provide adequate water for the plants. This suggests that tomatoes can efficiently utilise available water and nutrients without significant differences in growth or fruit production within this range. Additionally, the soil's physical and chemical properties can influence the retention and availability of water and nutrients to plants. If the soil has a strong water-holding capacity and nutrient retention, it might mitigate the effects of varying irrigation levels, leading to no significant differences ($p < 0.05$) in plant growth parameters. Moreover, the types of fertilising materials used might not have significantly differed in their nutrient compositions or release rates, leading to similar nutrient availability for the tomato plants regardless of the fertiliser type. This could result in no observable differences in growth and yield outcomes. The lack of significant differences might also stem from the experimental design, or the sensitivity of the measurements taken. The differences between treatments were too subtle or the sample size too small hence the experiment might not have detected significant effects. Lastly, the genetic makeup of the tomato plants used in the study could also influence the results. Some varieties are more tolerant of variations in water and nutrient availability, which could explain why changes in irrigation levels and fertilising materials did not significantly affect the measured growth parameters.

Water application and fertiliser significantly impact above-ground biomass, leaf area, the number of leaves, and dry fruit weight in plants (Jiao et al., 2012). Sufficient water availability is crucial for sustaining healthy leaves and promoting leaf enlargement. Proper watering supports overall plant growth by affecting leaf growth, increasing leaf area, and accumulating above-ground biomass. Water is a key component in photosynthesis, the process by which plants convert sunlight into energy and produce carbohydrates (Jiao et al., 2012). Adequate water supply during the flowering and fruiting stages is critical for fruit development and the accumulation of fruit weight. Proper irrigation ensures that the plant can transport nutrients to developing fruits, while water stress during this period can result in reduced fruit size and weight. Fertilisers provide essential nutrients, including N, P, and K, critical for plant growth and biomass production. N is essential for amino acids and proteins, which support cell division and leaf development and expansion, promoting vegetative growth, the development of new leaves, and increasing above-ground biomass. Therefore, adequate N supply can lead to an increased number of leaves. Fertilisers also supply essential nutrients like potassium and P, important for fruit development and maturation. Adequate nutrient supply through fertilisation can result in larger and heavier fruits.

5.3.7 Effect of treatment and Water application Elemental Composition of plant above ground Biomass

The comparative assessment of N and C content in different treatment groups—Cockerham Green, NP, Safisana, and unamended soil—is presented in Figures 5.7. The N content (Figure 5.5 Effect of water application and fertilising materials on the elemental carbon (%) and N (%) of plant biomass (ns -not significant $p>0.05$ Note: Values are mean of 5 replicates + SD) upper graph) and carbon content (Figure 5.5 Effect of water application and fertilising materials on the elemental carbon (%) and N (%) of plant biomass (ns -not significant $p>0.05$ Note: Values are mean of 5 replicates + SD) bottom graph) were measured under two irrigation treatments, 80 and

120 % WHC For N, the mean values across all treatment groups ranged narrowly between approximately 0.50 and 0.75 g/g.

The results for N content show relatively consistent values across different treatments and irrigation levels, ranging from approximately 0.55% to 0.70% (0.55g/g to 0.70g/g). There were no significant differences ($p > 0.05$) observed between treatments or between the two irrigation levels within each treatment. This suggests that neither the type of fertilising material used nor the level of irrigation within the tested ranges significantly influenced the nitrogen content in the plant biomass.

Similarly, the C content analysis across different treatments and irrigation levels showed a narrow range, primarily from 33% to 36%. As with nitrogen, these differences were not statistically significant ($p > 0.05$). This indicates a stable carbon percentage in plant biomass regardless of the fertilising material applied or the irrigation level.

The lack of significant differences in both nitrogen and carbon content across varying types of fertilising materials and water levels might indicate that the micro-Tom tomato plant species used in this experiment are relatively resilient or indifferent to these variations in terms of their elemental composition. This could be beneficial for agricultural practices in regions where water availability fluctuates, suggesting that certain crops might maintain their nutrient composition under varying cultivation conditions.

However, it is also possible that the duration of the treatment or the developmental stages of the plants were not sufficient to manifest changes in elemental content, or that the range of treatments was not broad enough to elicit a measurable response. Future research might explore longer treatment periods, different developmental stages, or a broader range of fertilising materials and irrigation levels to fully understand the dynamics between water application, fertilising materials, and elemental composition of plant biomass.

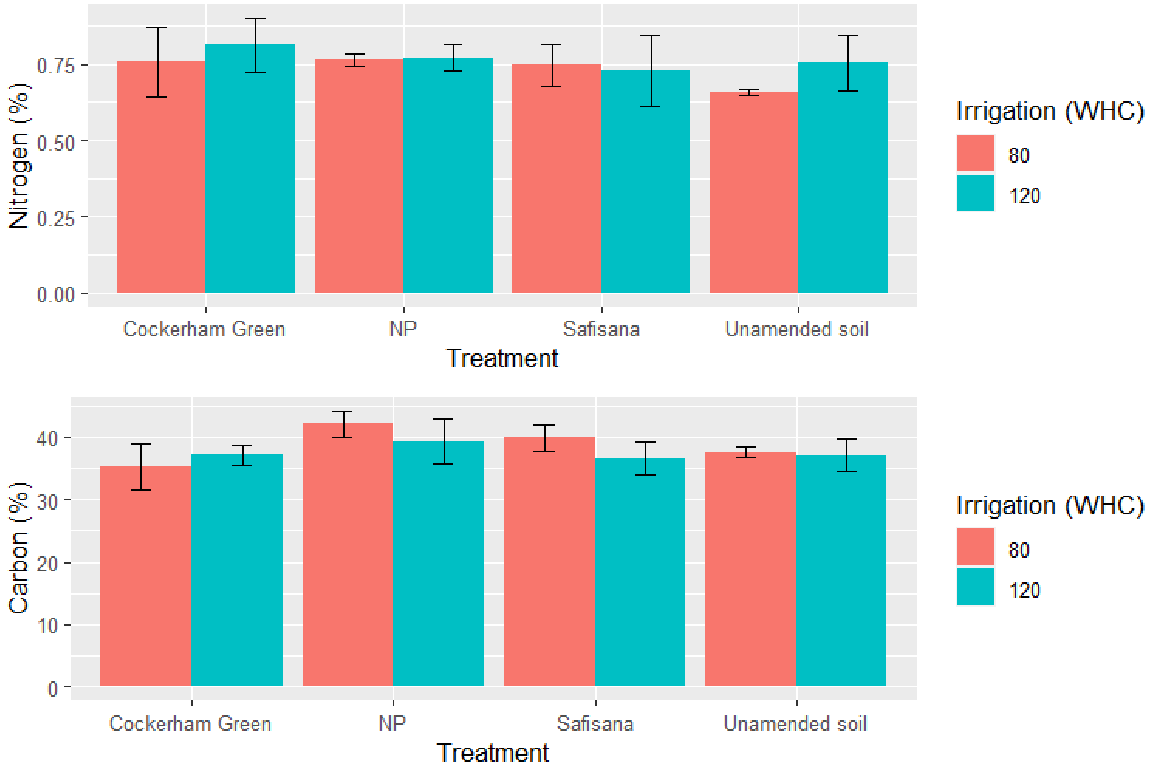

Figure 5.5 Effect of water application and fertilising materials on the elemental carbon (%) and N (%) of plant biomass (ns -not significant $p>0.05$ Note: Values are mean of 5 replicates + SD)

Fertilisation and water application significantly influence the elemental composition of plant biomass (Jiao, 2012; Głowacka et al., 2020). Fertilisers augment the soil with essential nutrients, thereby directly affecting the availability of these nutrients for plant uptake. N, a crucial component of chlorophyll, amino acids, proteins, and nucleic acids, plays a pivotal role in vegetative growth and metabolism (Jiao, 2012; Głowacka et al., 2020). When provided adequately, N fertilisation can enhance vegetative growth and bolster protein synthesis, which is reflected in increased N content within plant tissues. Similarly, the use of digestate or fertilising material is known to enrich the levels of macro and micronutrients such as P, K and S in plants, which are essential for energy transfer processes, DNA and RNA synthesis, and maintaining osmotic balance and enzyme functions (Camelin et al., 2021). While micronutrients are required in smaller quantities, they are equally important for various plant biochemical processes, and their inclusion in fertilisers can elevate their presence in plant biomass (Dhaliwal et al., 2022). Irrigation, on the other hand, regulates soil moisture levels and affects water content in plant tissues, including elements like hydrogen and oxygen. Proper irrigation is critical for maintaining cell turgor pressure and metabolic functions. It also facilitates the transportation of minerals from the soil to plant roots. Well-irrigated conditions can lead to a dilution effect of nutrients in plant biomass due to increased water content, while water stress may concentrate nutrients in plant tissues. Figure 5, although annotated as 'ns' (not significant), suggest that the differences in N and carbon content between the two irrigation levels within each treatment type are not statistically significant. This indicates that under the conditions of this experiment, the variations in irrigation levels did not lead to significant differences in the elemental composition of the plant biomass for both carbon and N content. It can be summarised that while fertilisation and water application are fundamental to influencing the elemental composition of plant biomass, the specific conditions of this experiment did not show significant variation in carbon and N content with changes in irrigation levels. This could imply that the range of irrigation levels tested were within a threshold that did not alter the elemental uptake, or the plants had adapted to utilise the available nutrients efficiently under both irrigation conditions.

5.3.8 Effects of fertiliser application and water application on Leachate pH

Figure 5. shows pH measurements across four leaching events for different treatments of Cockerham Green, Control, NP, and Safisana. The leachate events were observed for 120 % WHC of planted and unplanted conditions. The pH values for all treatments appeared to be consistently within the neutral range, hovering close to 6.3 to 6.5. There are no significant ($p > 0.05$) variations between the different leaching events within each treatment, indicating that neither the type of treatment nor the leaching event had a significant effect on the pH of the leachate. The error bars suggest that the variance within each set of measurements of five replicates is small, further supporting that pH remained stable across treatments and events.

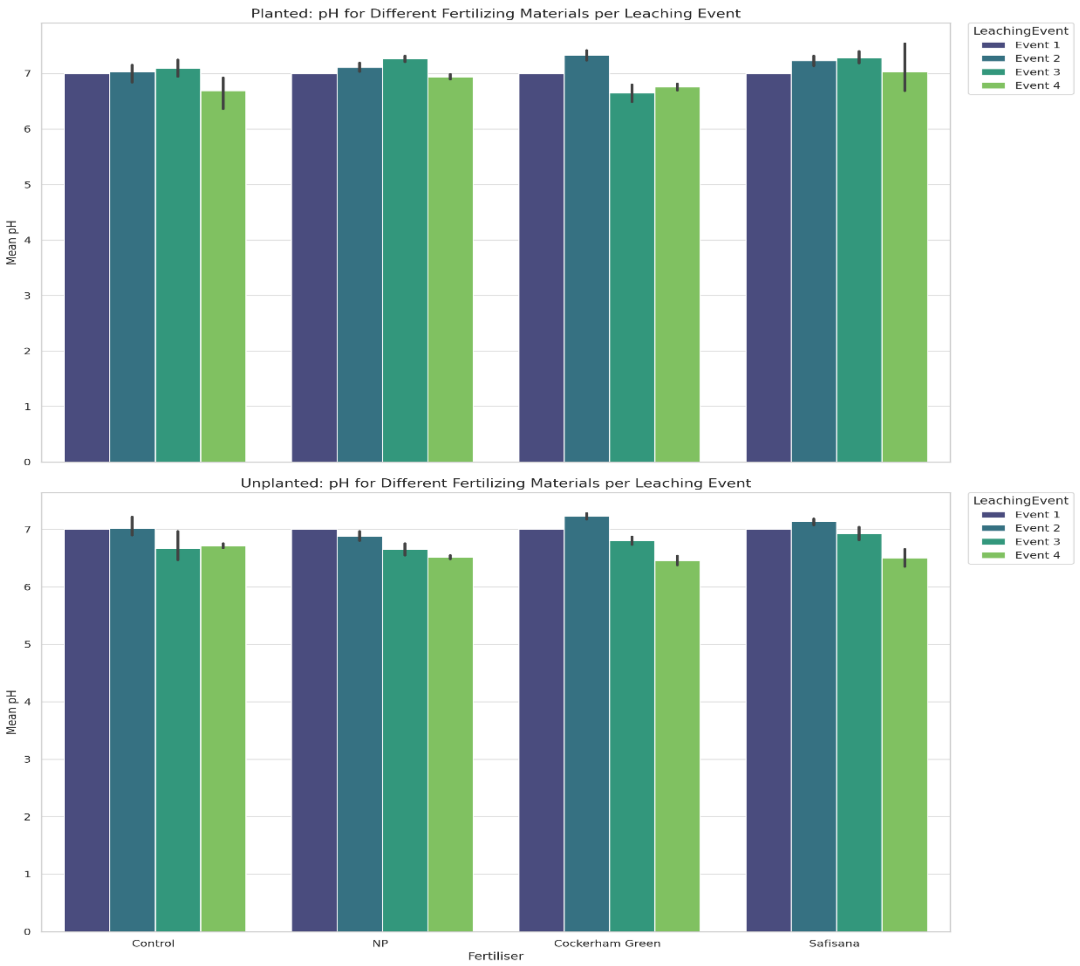

Figure 5.6 pH effect of water application and fertilising material

The statistical analysis to was conducted to examine the pH variations between Event 1 and subsequent leaching events within each distinct fertiliser treatment. The findings from this analysis are detailed as follows: Within the Control treatment group, a comparative analysis between Event 1 and Event 4 revealed a p-value of 0.0216 (P< 0.05), denoting a significant statistical difference. This outcome suggests a meaningful impact on the leaching event on pH of leachate. Comparisons involving other events within this treatment group did not yield statistically significant differences. For the NP treatment group, a notable statistical difference was observed between Event 1 and Event 4, as indicated by a p-value of 0.0002 (p<0.05). This signifies a significant alteration in the pH due to the leaching processes. In the situation of the Cockerham Green treatment, every comparative analysis with Event 1 elucidated significant differences. The most pronounced variation was noted at Event 4, where the p-value was less than 0.0001, underscoring a substantial effect on pH levels across the leaching events. Regarding the Safisana treatment group, significant differences were detected between Event 1 and Events 2 and 3, indicating impactful pH modifications due to leaching events. However, the comparison between Event 1 and Event 4 did not exhibit a significant difference, highlighting a variation in the treatment's effect over different leaching events.

5.3.9 Effects of fertiliser application and water application on Leachate EC

There were observable differences in electrical conductivity (EC) among the treatments over the course of four leaching events. It is important to note that EC can be influenced by acidity levels. During the first leaching event, there were no significant differences in EC across treatments. Notably, the second leaching event recorded higher EC values, especially in the control treatment, contrary to the initial description. The third leaching event exhibited variations in EC, although these were less pronounced than in the second event. The fourth leaching event did not show any major differences in EC among the treatments. Overall, NP and Cockerham Green displayed some variability in EC, while Safisana showed less fluctuation. The Control samples rarely indicated major differences.

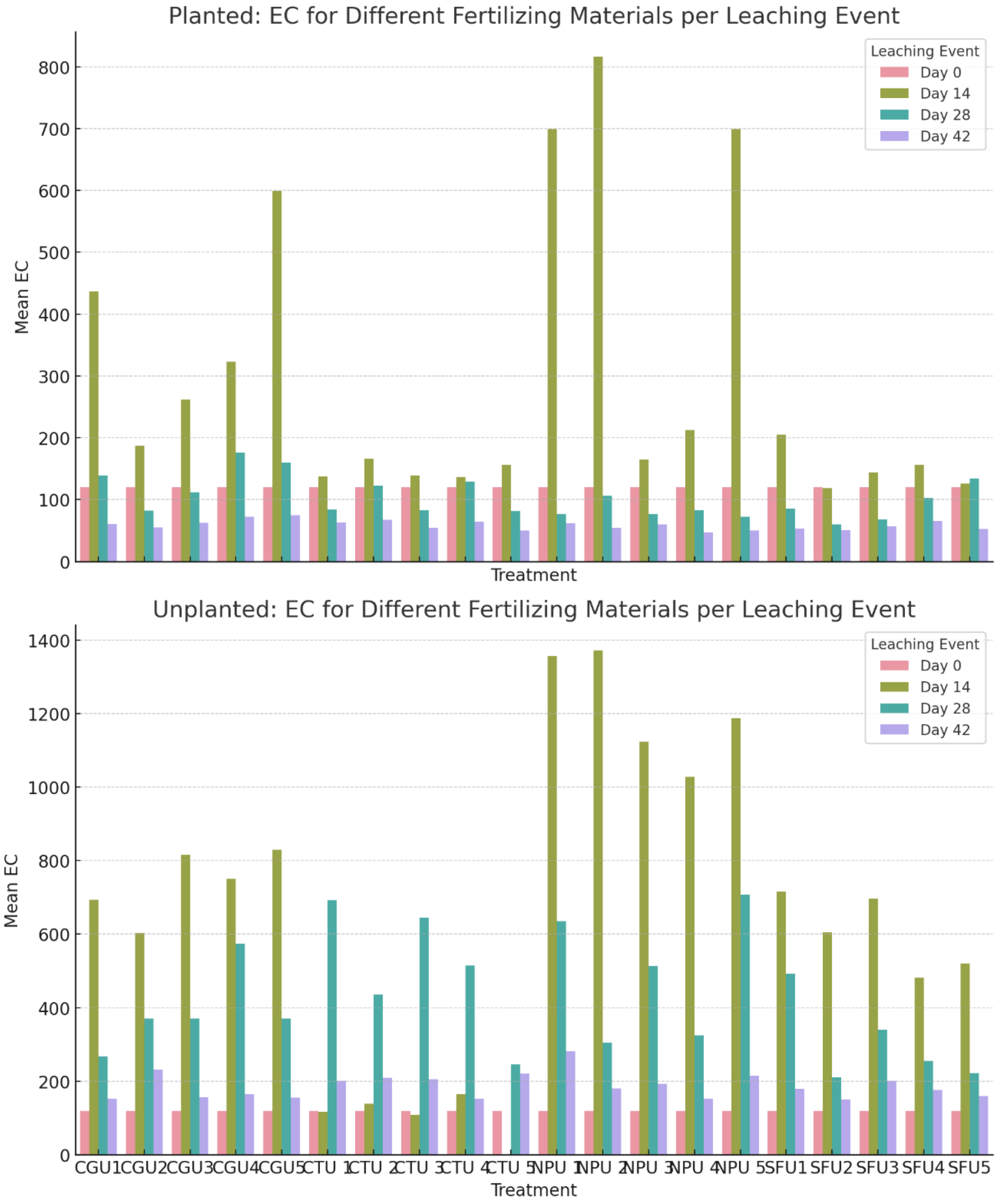

Figure 5.7: Effect of water application and fertilising materials on the Electrical Conductivity of soil solution.

Irrigation and fertiliser application can significantly affect soil pH and EC, which in turn, influence plant growth and nutrient availability (Zhang et al., 2023). Regular irrigation with pure, low-salt water can lower soil EC by diluting dissolved salts. While the direct effect of irrigation on soil pH is minimal, the pH of the irrigation water can alter soil pH over time. Excessive irrigation may result in leaching of components that contribute to pH levels, thus affecting the soil pH. Fertilisers impact soil pH differently. Ammonium-based fertilisers tend to lower soil pH as the ammonium (NH_4) is converted to nitrate (NO_3), releasing hydrogen ions into the soil (Midden et al., 2023). In contrast, fertilisers containing lime or calcium carbonate raise soil pH by neutralising acidity, a method often employed to amend acidic soils (Athanase et al., 2013). Additionally, fertilisers can affect soil EC, thus saline fertilisers increase EC by adding soluble salts to the soil, whereas organic fertilisers typically have a negligible impact on EC unless they are applied in large quantities or contain salts (Hirzel et al., 2018). The type and quantity of fertiliser applied can modify the availability of nutrients to plants. Shifts in pH and EC can alter the solubility and mobility of nutrients, potentially enhancing or inhibiting their uptake by plants.

5.4 Conclusion

This study investigated the impacts of various fertilisers and irrigation regimes on the growth, yield, and soil properties of micro-Tom tomatoes, generally revealing no significant differences across treatments. This outcome suggests the plant's resilience or adaptability to diverse nutritional and water inputs, indicating that micro-Tom tomatoes can thrive under a wide range of conditions without notable variations in growth outcomes or soil health. The absence of significant differences could point to the plants' evolutionary mechanisms for optimising resource utilisation or indicate that experimental conditions were already within optimal growth parameters. This highlights the complexity of plant responses to environmental inputs and the existence of a potential saturation point in resource use efficiency.

The findings advocate for a customised approach to fertilisation and irrigation, underlining the importance of understanding plant-environment interactions for developing sustainable agricultural practices that efficiently use resources, minimise environmental impacts, and sustain crop productivity. The study's design limitations, including the choice of fertilising materials, irrigation regimes, sample size, experiment duration, and measurement sensitivity, suggest areas for future research to refine experimental approaches. Further investigation into plant growth dynamics, through long-term studies and exploration of a broader range of fertilising materials and environmental interactions, could provide deeper insights into optimising agricultural practices for enhanced plant growth and sustainability.

5.5 Supplementary Information for Chapter 5

5.5.1 Statistical Analysis of Growth parameters of Chapter 5

No.	Irrigation based on WHC	Y	Group 1	Group2	N1	N2	statistic	df	P	significance
1	80	Aboveground biomass	Cockerham Green	NP	5	5	-0.823	7.97	0.434	Ns
2	80	Aboveground biomass	Cockerham Green	Safisana	5	5	1.03	6.76	0.336	Ns
3	80	Aboveground biomass	Cockerham Green	Unamended soil	5	5	0.831	7.34	0.432	Ns
4	80	Aboveground biomass	NP	Safisana	5	5	2.07	6.99	0.461	Ns
5	80	Aboveground biomass	NP	Unamended soil	5	5	1.81	7.54	0.55	Ns
6	80	Aboveground biomass	Safisana	Unamended soil	5	5	-0.2	7.83	0.847	Ns
7	120	Aboveground biomass	Cockerham Green	NP	5	5	-0.764	7.99	0.467	Ns
8	120	Aboveground biomass	Cockerham Green	Safisana	5	5	-0.222	6.44	0.831	Ns
9	120	Aboveground biomass	Cockerham Green	Unamended soil	5	5	0.362	6.62	0.729	Ns
10	120	Aboveground biomass	NP	Safisana	5	5	0.714	6.55	0.5	Ns
11	120	Aboveground biomass	NP	Unamended soil	5	5	1.3	6.73	0.237	Ns
12	120	Aboveground biomass	Safisana	Unamended soil	5	5	0.807	7.98	0.443	Ns
13	80	Fruit DW	Cockerham Green	NP	5	5	-1.3	7.75	0.23	Ns
14	80	Fruit DW	Cockerham Green	Safisana	5	5	1.43	7.27	0.196	Ns
15	80	Fruit DW	Cockerham Green	Unamended soil	5	5	1.05	7.87	0.324	Ns
16	80	Fruit DW	NP	Safisana	5	5	2.71	6.56	0.032	*
17	80	Fruit DW	NP	Unamended soil	5	5	2.31	7.35	0.05	*
18	80	Fruit DW	Safisana	Unamended soil	5	5	-0.312	7.7	0.764	Ns
19	120	Fruit DW	Cockerham Green	NP	5	5	-0.716	7.75	0.495	Ns
20	120	Fruit DW	Cockerham Green	Safisana	5	5	0.486	5.57	0.646	Ns
21	120	Fruit DW	Cockerham Green	Unamended soil	5	5	0.814	5.52	0.449	Ns
22	120	Fruit DW	NP	Safisana	5	5	1.54	6.16	0.172	Ns
23	120	Fruit DW	NP	Unamended soil	5	5	1.93	6.11	0.101	Ns
24	120	Fruit DW	Safisana	Unamended soil	5	5	0.566	8	0.587	Ns
25	80	No of Leaves	Cockerham Green	NP	5	5	-2.55	6.91	0.039	*
26	80	No of Leaves	Cockerham Green	Safisana	5	5	-0.941	7.56	0.376	Ns
27	80	No of Leaves	Cockerham Green	Unamended soil	5	5	0.299	6.67	0.774	Ns

28	80	No of Leaves	NP	Safisana	5	5	2.01	5.98	0.091	Ns
29	80	No of Leaves	NP	Unamended soil	5	5	3.04	5.29	0.027	*
30	80	No of Leaves	Safisana	Unamended soil	5	5	1.55	7.6	0.162	Ns
31	120	No of Leaves	Cockerham Green	NP	5	5	1.67	6.8	0.141	Ns
32	120	No of Leaves	Cockerham Green	Safisana	5	5	-0.591	7.93	0.571	Ns
33	120	No of Leaves	Cockerham Green	Unamended soil	5	5	-0.37	6.81	0.723	Ns
34	120	No of Leaves	NP	Safisana	5	5	0.863	6.42	0.419	Ns
35	120	No of Leaves	NP	Unamended soil	5	5	1.7	8	0.127	Ns
36	120	No of Leaves	Safisana	Unamended soil	5	5	0.345	6.43	0.741	Ns
37	80	Leaf Area	Cockerham Green	NP	5	5	-3.39	7.92	0.01	*
38	80	Leaf Area	Cockerham Green	Safisana	5	5	-0.625	6.67	0.553	Ns
39	80	Leaf Area	Cockerham Green	Unamended soil	5	5	0.717	6.06	0.5	Ns
40	80	Leaf Area	NP	Safisana	5	5	3.41	6.28	0.013	*
41	80	Leaf Area	NP	Unamended soil	5	5	4.79	5.72	0.003	*
42	80	Leaf Area	Safisana	Unamended soil	5	5	1.9	7.8	0.095	Ns
43	120	Leaf Area	Cockerham Green	NP	5	5	-3.1	7.99	0.015	*
44	120	Leaf Area	Cockerham Green	Safisana	5	5	-0.441	6.98	0.673	Ns
45	120	Leaf Area	Cockerham Green	Unamended soil	5	5	-0.331	6.68	0.751	Ns
46	120	Leaf Area	NP	Safisana	5	5	1.98	6.83	0.09	Ns
47	120	Leaf Area	NP	Unamended soil	5	5	1.96	6.54	0.094	Ns
48	120	Leaf Area	Safisana	Unamended soil	5	5	0.0751	7.96	0.942	Ns

6 General Conclusions and Future Directions

6.1 Synthesis and summary of aims and objectives.

This research embarked on a comprehensive exploration of the potential benefits and applicability of anaerobic digestate, a by-product of the anaerobic digestion process, as an organic fertiliser in comparison to traditional mineral fertilisers. Focused on the context of Sub-Saharan Africa (SSA), where agricultural sustainability and soil fertility are pressing issues, this study aimed to contribute to the existing body of knowledge by providing empirical evidence on the viability of digestate to improve soil health, soil fertility and crop productivity, particularly for tomato cultivation under different environmental conditions.

This discussion will give a general overview of the key results of this thesis, followed by reflection into the broader implications of the findings including what they mean for the future of digestate use in different environmental conditions. It will go into detail about the limitations of the research presented and unanswered questions which have arisen from the findings of this thesis, and how they could be addressed or improved in future work. Finally, there are the final conclusions to this thesis.

To investigate the impacts of digestate use in different environmental conditions the following objectives were set:

1. Extensively explore and evaluate the resource recovery from waste streams in Sub-Saharan Africa (SSA) including methods, technologies, and existing policies of waste safety, as well as the environmental impact, and socio-economic implications of recovered fertilisers (Chapter 2).

2. Evaluate the feasibility of replacing chemical fertilisers with digestate from different sources (Ghana and UK) using the micro-Tom tomato cultivar in sandy Podzols through a growth experiment (Chapter 3).

3. Evaluate how different doses of digestate (ranging from 22.5 to 90 kg N/ha) affect nutrient cycling in two distinct soil types, namely sandy podzols and *Ferric Acrisol* through the monitoring of pysio-chemical properties and microbial biomass b. Determine the optimal digestate application rate for balanced nutrient cycling in different soil environments (Chapter 4).

4. Study the effects of digestate application (based on a total N dose of 90Kg N/ha) under two different irrigation regimes on the growth and yield of tomatoes. b. Compare these effects with those observed in plants grown with urea and in unamended soil, considering the soil under planted and unplanted conditions. c. Assess water-use efficiency and yield quality under varying conditions of nutrient and water availability (Chapter 5).

6.2 Summary of Key Findings

Through literature and experimental investigations across chapters two to five, this thesis highlighted the effectiveness of digestate as a sustainable alternative to chemical fertilisers. Key findings across the chapters revealed.

6.2.1 Producing safe and sustainable fertiliser in SSA through organic waste resource recovery.

Chapter two began with a comprehensive investigation of the environmental challenges confronting Sub-Saharan Africa (SSA) and examines the potential for organic waste recovery as a sustainable solution. It outlines the dual aspects of organic waste management in SSA - the problems and opportunities, particularly emphasising the transformation of waste into valuable resources for sustainable agriculture, contingent upon rigorous treatment processes to ensure safety and quality. The success of waste-to-fertiliser initiatives pivots on the integration of technological innovations, community involvement, policy frameworks, and tailored business strategies, emphasising on the need of adapting these elements to the specificities of local contexts.

The core theoretical examination within this chapter focuses on digestate, a by-product of the anaerobic digestion process, which breaks down organic material in an oxygen-free environment, resulting in biogas and a nutrient-rich organic fertiliser. The AD process accompanied by digestate is highlighted for its critical role in curbing greenhouse gas emissions through untreated wastes. The use of digestate is also noted with enhancing soil quality, mitigating soil degradation, and curbing GHG associated with synthetic fertiliser production. The nutrient-rich profile of digestate, incorporating N, P, and K, is recognised for its capacity to enhance soil fertility and boost agricultural output. Additionally, the chapter delves into the strategic use of digestate as a soil amendment, advocating for its role in diminishing reliance on synthetic fertilisers, thus contributing to a circular economy and sustainable agricultural practices in SSA.

Beyond its nutrient contribution, Chapter two further discusses digestate's supplementary benefits, including its positive impact on soil structure, moisture retention, and microbial activity, positioning it as a viable alternative to chemical fertilisers. It promotes healthier plant growth and increased crop yields. However, the chapter advises careful management of digestate application in terms of timing, quantity, and technique to leverage its advantages fully while mitigating potential risks, such as nutrient runoff or phytotoxicity (Kebalo et al., 2024).

This theoretical exploration in Chapter two underlines the significance of digestate from anaerobic digestion as a key element in fostering sustainable agricultural practices in SSA, where there is a rising demand for environmentally sound and efficient farming methodologies.

6.2.2 Assessing the fertilising property of different anaerobic digestates on early growth and development of a dwarf tomato cultivar

Chapter three of this thesis focuses on the comparative analysis of the fertilising properties of different anaerobic digestates on the early growth and development of a micro- Tom, a dwarf tomato cultivar. This chapter examines the impact of digestates derived from municipal, agricultural, and food waste streams in the UK and Ghana on micro-tom tomato growth in low-nutrient, acidic sandy Podzols. Through a well-structured experimental design, digestate treatments from Cockerham green, ISR = 2.0, and Safisana were applied at a rate of 100 kg N/ha, alongside urea (positive control) and unamended soils (negative control). The study meticulously measures growth parameters such as plant height, stem diameter, number of leaflets, total leaf area, and chlorophyll content, alongside the dry weight of above-ground biomass, to evaluate the digestates' effectiveness compared to mineral urea fertilisation and control conditions.

The research finds that digestate and mineral urea fertilisation significantly enhance tomato growth and soil nitrogen availability over unamended treatments. Among the digestate treatments, varying effects on soil chemical properties such as pH, EC and plant growth parameters were observed, indicating differences in nutrient release patterns and bioavailability. Urea treatments generally produced higher plant biomass, attributing to the more readily available form of nitrogen. However, digestates also showed considerable potential in supporting tomato growth, offering a sustainable alternative to conventional mineral fertilisers by enhancing soil fertility and plant nutrient uptake.

In Chapter 3, there was no significant difference in soil pH and EC between treatments with digestate and chemical fertilisers, suggesting digestate can maintain soil health comparable to traditional fertilisers.

- Digestate and urea treatments led to a significant increase in the number of leaflets and total leaf area of tomato plants, indicating a positive impact on plant growth.

- The chlorophyll content, a marker of nutrient status, did not show significant differences between digestate and urea treatments, supporting the nutrient efficacy of digestate.
- there was significant evidence to support the potential of digestate to replace mineral fertilisers. The key finding was that digestate provided a nutrient-rich alternative capable of supporting the early growth and development of micro-Tom tomato plants. Specifically, results showed that digestate led to significantly higher values in morphology and dry plant above-ground biomass compared to unamended soils.
- Even when applied at the same total nitrogen (TN) application rate as mineral fertilisers, plants treated with digestate performed comparably, indicating that the TN in digestate, partly in plant-available form, was effectively utilised by the plants. Additionally, the addition of digestate increased the available nitrogen content compared to the unamended soils, further suggesting its efficacy as a fertiliser.
- Thus, it can be concluded that digestate can support the early growth and development of micro-Tom tomato plants, offering a viable, sustainable alternative to mineral fertilisers.

6.2.3 Effects of Digestate additions on the cycling of Nitrogen and Phosphorus in soils

Chapter four elucidates the impacts of digestate additions on the cycling of nitrogen, and phosphorus in soils, presenting a detailed investigation into the role of organic amendments in enhancing soil nutrient dynamics and microbial activity. Utilising soils from two distinct environments—*Ferric Acrisol* from Ghana and sandy Podzols from the UK—the study embarked on a soil incubation experiment to assess changes in soil properties and nutrient dynamics over a 90-day period with varying rates (22.5KgN/ha – 90 Kg N/ha) of digestate application. The comprehensive methodological approach included initial soil and digestate characterisations, experimental design, and rigorous statistical analysis, ensuring a robust evaluation of digestate's effectiveness as a soil amendment.

The findings reveal significant modifications in soil chemical properties, including pH, EC, and available nitrogen (NO_3^--N and NH_4^+-N) and P levels, attributed to digestate application. Notably, the study demonstrates digestate's capacity to increase soils essential nutrient availability, notably NO_3^--N, NH_4^+-N and inorganic P, while also enhancing microbial biomass carbon, nitrogen, and phosphorus. These outcomes underscore the potential of digestate to serve as a viable organic fertiliser, contributing to sustainable soil management practices.

The study found that different doses of digestate affected soil pH, EC, and available nitrogen (NO_3^--N and NH_4^+-N), with significant impacts observed at higher doses of 90 kg N/ha. Soil microbial biomass nitrogen (MBN) did not follow a specific pattern across different treatments or soil types, indicating that the activity was not solely dependent on the type of fertilising material or soil type. Furthermore, the research highlights the nuanced response of different soil types to organic amendments, with variations in nutrient dynamics and microbial activity observed between Ferric Acrisol and sandy Podzols.

The change in soil pH can significantly affect nutrient availability, microbial activity, and overall soil health. An optimal pH range is crucial for the effective utilisation of nutrients by plants. The digestate's influence on pH suggests it can be used to modify soil pH towards a more favourable condition for specific crops, although care must be taken to avoid adverse effects from over-application.

The observed changes in EC, particularly with higher digestate doses, indicate an increase in soil mineral content, specifically salts. While EC is a measure of soil's ability to conduct electrical current, reflecting the level of soluble salts, it's also an indirect indicator of nutrient availability. High EC levels can lead to salinity issues, affecting plant growth negatively. However, moderate increases can enhance nutrient supply to plants. The finding suggests that while digestate can improve nutrient availability, its application rate must be managed to prevent potential salinity stress on crops.

The increase in available nitrogen (NO_3^--N and NH_4^+-N) with the application of digestate is a key finding, highlighting digestate's potential as a nitrogen-rich fertiliser. Nitrogen is a critical nutrient for plant growth, influencing processes like photosynthesis and protein synthesis. The ability of digestate to supply readily available nitrogen can support crop productivity and reduce the need for synthetic nitrogen fertilisers, aligning with sustainable agriculture goals.

The lack of a consistent pattern in MBN across treatments and soil types suggests that digestate's impact on soil microbial communities is complex. MBN is a measure of the microbial community's ability to store and cycle nitrogen within the soil. This finding indicates that while digestate provides nitrogen and other nutrients, the response of microbial communities may be influenced by other factors such as soil physical properties, existing microbial populations, and environmental conditions. The role of soil microbes in nutrient cycling, disease suppression, and soil structure maintenance is vital for sustainable agricultural systems. Thus, understanding how digestate influences these microbial communities is crucial for optimising its use as an organic fertiliser.

These findings from Chapter four highlight the multifaceted effects of digestate application on soil health and function. The ability of digestate to alter soil pH, increase EC, and enhance nitrogen availability (NO_3^--N and NH_4^+-N) positions it as a valuable resource for sustainable agriculture practices. However, the complex interactions with soil microbial communities highlight the need for further research to optimise digestate application rates and methods to harness its full potential as an organic fertiliser. Ultimately, these insights contribute to the growing body of knowledge supporting the integration of waste-derived organic amendments into farming systems, promoting circular economy principles, and reducing reliance on chemical fertilisers.

6.2.4 Impact of Water Application Rates on Tomato Growth with Digestate and Mineral Fertiliser

Chapter five delves into the comparative effectiveness of anaerobic digestate (AD) from Ghana and the UK and mineral fertilisers on the growth, yield, and soil properties of micro-Tom tomatoes under varied water regimes. Conducted in a controlled glasshouse setting, this research aims to illuminate AD's potential as a nutrient-rich organic fertiliser derived from waste management processes and its implications for sustainable agricultural practices, particularly in nutrient-poor sandy soils.

Employing a detailed methodology, the study assesses the impact of fertiliser types (digestate and Urea - Phosphate (NP)) and water application regimes over 70 days. It meticulously measures key parameters such as nutrient availability, chlorophyll content, photosynthetic efficiency, above-ground biomass, leaf area, number of leaves, and fruit yield. Despite AD's theoretical benefits in enhancing soil fertility and promoting plant growth, the findings reveal no significant differences in plant growth and productivity between AD and mineral fertiliser treatments across different water regimes. This suggests the micro-Tom tomato cultivar's remarkable resilience to various fertilisation strategies and environmental conditions, underscoring AD's wider application potential in sustainable agriculture.

Moreover, the study investigates the effects of fertilisation and irrigation on soils leachate properties like pH, EC, offering insights into the environmental impact of using AD as a fertiliser. The absence of significant differences in these soil properties across treatments indicates digestate compatibility with sustainable farming, highlighting the importance of optimised management strategies for enhancing agricultural productivity while minimising environmental impacts.

The research also shows that digestate and mineral fertilisers support tomato cultivation equally well under different water application regimes, emphasising digestate's viability as a sustainable fertiliser alternative. The lack of significant differences in plant growth and yield suggests that digestate can effectively replace synthetic fertilisers without compromising crop production. This outcome is particularly relevant for areas with variable water availability, indicating that digestate could be used to maintain productivity with fluctuating water supplies, offering benefits of resource efficiency and environmental sustainability.

The study's findings that digestate-treated plants achieve similar productivity levels to those treated with mineral fertilisers across varying water regimes also point to efficient water use in digestate-amended soils. This efficiency is vital in regions facing water scarcity, suggesting that adopting organic fertilisers like digestate could contribute to more sustainable water management in agriculture without sacrificing crop yields.

By highlighting digestate’s effectiveness as a fertiliser under diverse water application rates, this chapter strengthens the case for a circular economy in agricultural practices. Utilising waste-derived products like digestate not only recycles nutrients but also reduces farming's environmental footprint, showcasing a practical approach to sustainable waste management. The capacity of digestate to support crop growth as effectively as mineral fertilisers, even with variable water supplies, highlights its potential to lessen agriculture's reliance on synthetic inputs. This shift could yield long-term benefits, including reduced soil and water contamination, lower production costs for farmers, and decreased greenhouse gas emissions associated with the production and application of chemical fertilisers.

Chapter 5's exploration of the interaction between digestate application and water regimes presents promising avenues for incorporating organic waste products into agricultural systems. By sustaining productivity under varied watering conditions, digestate use in crop cultivation emerges as a sustainable practice aligned with global efforts to mitigate climate change impacts and promote resource conservation. Future research could further investigate the mechanisms behind the observed water-use efficiency in digestate-amended soils and expand these findings to other crops and climates, deepening the understanding of organic fertilisers' role in sustainably achieving global food security.

6.3 Implications for Agricultural Sustainability in SSA

Expanding on the implications for agricultural sustainability in Sub-Saharan Africa (SSA) based on the comprehensive findings from all chapters of this thesis, it's clear that the utilisation of digestate as an alternative to mineral fertilisers presents a multifaceted opportunity to address several critical challenges in the region. These implications not only underline the environmental benefits but also highlight the socio-economic and agronomic advantages, contributing to a holistic approach towards sustainable development in SSA's agricultural sector (Boon & Anuga, 2020).

6.3.1 Enhancing Soil Health and Crop Productivity

Across the chapters, the research underscores the potential of digestate to improve soil health by supplying essential nutrients particularly NO_3^--N and NH_4^+-N and organic matter. This is particularly crucial in SSA, where many regions suffer from degraded soil conditions due to intensive farming practices, erosion, and nutrient depletion. The ability of digestate to replenish soil nutrients and improve soil structure can lead to enhanced water retention, aeration, and microbial activity, which are vital for crop productivity. Such improvements in soil health can significantly increase agricultural output, thereby contributing to food security and rural livelihoods.

6.3.2 Promoting Circular Economy and Environmental Sustainability

The findings from the thesis support a shift towards circular economy models in waste management and agriculture by demonstrating the value of converting organic waste into digestate for agricultural use. This approach not only reduces the environmental footprint associated with waste disposal and chemical fertiliser production but also enhances resource efficiency by recycling nutrients back into the farming system. By adopting circular economy practices, SSA can mitigate greenhouse gas emissions, preserve natural resources, and enhance biodiversity, aligning with global environmental sustainability goals.

6.3.3 Reducing Dependence on Chemical Fertilisers

The comparable efficacy of digestate and mineral fertilisers in supporting plant growth and yield, as shown in the research (Chapter 3 and Chapter 5), provides a compelling argument for reducing reliance on chemical fertilisers. This is particularly relevant for SSA, where the cost and availability of chemical fertilisers can be expensive for smallholder farmers. The use of digestate offers an accessible and sustainable fertiliser option, potentially reducing input costs and increasing the resilience of farming systems to market fluctuations and supply chain disruptions.

6.3.4 Adapting to Climate Variability and Enhancing Resilience

The versatility of digestate application under different environmental and climatic conditions, as demonstrated in the research, indicates its potential to support agriculture in SSA's diverse agro-ecological zones. By providing a sustainable fertiliser option that can be adapted to varying water regimes and soil types, digestate use can enhance the resilience of farming systems to climate variability and change. This adaptability is crucial for SSA, where climate change poses a significant risk to agricultural productivity and food security.

6.3.5 Fostering Socio-economic Development

By integrating waste-to-resource strategies such as the production and use of digestate in agriculture, SSA can stimulate socio-economic development through job creation in the waste management and agricultural sectors (Boon & Anuga, 2020). This approach can also support rural economies by increasing agricultural productivity and profitability, thereby reducing poverty, and enhancing food security.

6.4 Directions for Future Research

While this thesis has laid a foundation for the use of digestate in sustainable agriculture, several avenues for future research have emerged:

i. Long-term studies on the impact of digestate application on soil microbial diversity, structure, and function to understand its broader ecological effects.

ii. Comparative analyses of digestate effects on a wider range of crops to generalise the findings and recommendations for its application in SSA.
iii. Investigations into the socio-economic barriers and enablers for the adoption of digestate by local farmers, including policy, market, and educational aspects.

Expanding on the directions for future research based on the comprehensive findings from all chapters of the thesis, can help delve deeper into several critical areas that could further enhance the understanding of digestate's role in sustainable agriculture, particularly within the context of Sub-Saharan Africa (SSA). Here are elaborated directions for future research (below):

6.4.1 Long-term Ecological Impact Studies

The thesis has initiated the exploration of digestate's potential as a sustainable fertiliser alternative. Future research should focus on long-term studies to assess the long-term impacts of digestate application on soil health, including changes in microbial diversity, soil structure, and function. Understanding the collective effects of repeated digestate applications over multiple growing seasons will provide insights into its sustainability as a soil amendment and its broader ecological effects, such as:

i. The potential for soil carbon sequestration and its implications for climate change mitigation.
ii. The resilience of soil microbial communities to changes in nutrient cycling and potential shifts in soil biodiversity.

iii. The impact on soil physical properties, including porosity, aggregate stability, and water retention capacity, which influence plant growth and soil erosion.

6.4.2 Crop-Specific Research

While the thesis presents compelling evidence of digestate's efficacy for micro- Tom tomato cultivation, expanding this research to include a broader spectrum of crops is essential. Comparative studies across various crops—both staple and cash crops prevalent in SSA—will help generalise the findings and optimise digestate application rates and methods for different agricultural systems. This includes:

i. Investigating digestate's effects on legumes, cereals, root crops, and horticultural species, which play pivotal roles in SSA's food security and economy.
ii. Assessing the potential for digestate to meet the specific nutrient requirements of these crops, considering their varying stages of growth and development.
iii. Exploring the interactions between digestate application and crop resistance to pests and diseases, which can significantly affect yield and quality.

6.4.3 Socio-economic and Policy Research

Understanding the socio-economic barriers and facilitators to the adoption of digestate as a fertiliser by local farmers is crucial for its successful integration into SSA's agricultural practices. This entails:

i. Conducting socio-economic analyses to evaluate the cost-effectiveness of digestate use compared to chemical fertilisers, including the initial investment required for anaerobic digestion facilities.
ii. Investigating the policy and regulatory landscape affecting digestate production and use, identifying gaps or challenges that may hinder its adoption, and proposing policy recommendations to support its integration.
iii. Exploring educational and extension services to raise awareness among farmers about the benefits and application techniques of digestate, addressing misconceptions, and providing practical guidance.

6.4.4 Market and Supply Chain Analyses

Further research should also examine the market dynamics and supply chain logistics for digestate, considering:

i. The potential for creating a viable market for digestate, including demand assessment, pricing strategies, and marketing channels.
ii. The logistics of digestate production, storage, and distribution, ensuring it is accessible to farmers across SSA, including remote and smallholder farms.
iii. The development of business models that can support the sustainability of digestate production and use, fostering partnerships between waste management sectors and agriculture.

By addressing these future research directions, can help build upon the foundation laid by this thesis to fully harness digestate's potential as a sustainable fertiliser, contributing to the advancement of circular economy practices in agriculture and enhancing food security and environmental sustainability in Sub-Saharan Africa.

6.5 Contributions and implications for sustainable agriculture in Sub-Saharan Africa (SSA)

Building on the comprehensive insights gathered from all chapters, the conclusion of this thesis can be expanded to encapsulate the multifaceted contributions and implications for sustainable agriculture in Sub-Saharan Africa (SSA) through the lens of digestate use as an organic fertiliser. This research marks a pivotal advancement in the quest for sustainability within agricultural systems, offering tangible solutions to some of the most pressing challenges facing SSA today.

6.5.1 Environmental Contributions

This thesis has demonstrated that digestate, as a by-product of anaerobic digestion, can play a crucial role in enhancing soil health and agricultural productivity while mitigating environmental degradation (Chapter 4). By recycling organic waste into a valuable fertiliser, it reduces the environmental footprint associated with waste disposal and chemical fertiliser production (Sharma et al., 2019). The findings underscore the ecological benefits of closing nutrient cycles, reducing greenhouse gas emissions, and conserving natural resources, thereby contributing to the sustainability goals of reducing environmental impact.

6.5.2 Economic Implications

The utilisation of digestate provides a cost-effective alternative to chemical fertilisers, potentially lowering the financial barriers to sustainable farming practices for smallholder farmers in SSA (Ndambi et al., 2019; Singh et al., 2022). This thesis highlights the economic viability of digestate by showcasing its efficacy in supporting crop growth and yield, comparable to traditional fertilisers (Jones & Vale, 2009). By leveraging locally available organic waste, communities can foster a more self-sufficient agricultural model, reducing dependence on imported fertilisers and enhancing the resilience of rural economies against external shocks (Boon & Anuga, 2020).

6.5.3 Advancing Food Security

In SSA where food security remains a critical concern, the ability of digestate to support crop productivity is of paramount importance (Tolessa, 2024). This research contributes valuable knowledge towards developing more productive, resilient agricultural systems capable of feeding a growing population under changing climatic conditions. By improving soil fertility and crop yields through sustainable means, digestate use can be a cornerstone in the strategy to combat food insecurity in SSA, ensuring access to nutritious food for all (Tolessa, 2024).

6.5.4 Strengthening Resilience and Sustainability

The findings from this thesis advocate for an integrated approach to waste management (Chapter 2) and agriculture (Chapter 3 and Chapter 5), aligning with the principles of a circular economy (Chapter 1). In showcasing the practicality and benefits of digestate application, this work encourages the adoption of practices that not only bolster agricultural sustainability but also enhance ecosystem resilience. The transition towards circular agricultural systems is essential for facing the dual challenges of environmental degradation and climate change, providing a blueprint for sustainable development in SSA and beyond.

6.6 Conclusion

In conclusion, this thesis represents a significant stride towards realising sustainable agricultural practices in SSA through the innovative use of digestate as an organic fertiliser. It bridges gaps in knowledge, challenges existing paradigms, and opens new avenues for research and application. While the journey towards fully sustainable agriculture in SSA is ongoing and complex, the insights offered by this research illuminate the path forward, contributing to the global mission of achieving sustainability and resilience in food systems. The continued exploration and adoption of such practices will be crucial in shaping a sustainable, food-secure future for SSA and the world.

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