Napier Grass Productivity and Selected Quality Parameters of a Degraded Soil in Response to Entrenched Nappies and *Acacia mearnsii* Biochar in South Africa

Ayanda Shandu

Bachelor of Science in Agriculture (Soil Science)

Submitted in fulfilment of the requirements for Master of Science in Agriculture

(Soil Science)

School of Agriculture, Earth, and Environmental Sciences

Discipline of Soil Sciences

University of KwaZulu-Natal

Pietermaritzburg

South Africa

February 2025

DECLARATION 1 - PLAGIARISM

I, **Ayanda Lucky Shandu**, declare that

1. The research reported in this thesis, except where otherwise indicated, is my original research.

2. This thesis has not been submitted for any degree or examination at any other university.

3. This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

4. This thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

a. Their words have been re-written, but the general information attributed to them has been referenced

b. Where their exact words have been used, then their writing has been placed in italics and inside quotation marks and referenced.

5. This thesis does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the thesis and in the References sections.

Signed: ……...Date: 6-Feb-2025

Candidate: Ayanda Shandu

I certify that the above statement is correct and as the candidate's supervisor, I have approved this thesis for submission.

Signe…….. …… Date…06/02/2025….

Supervisor: Professor Pardon Muchaonyerwa

ACKNOWLEDGEMENTS

I would like to thank God and the Ancestors for pushing me until the end of this project. My endless gratitude and acknowledgements go to:

- Joint Nature Conservation Committee (JNCC) and the Institute of Natural Resources (INR) for the project, funding and tremendous support.
- My Supervisor, Prof. Pardon Muchaonyerwa for identifying me for the study, his unlimited wisdom and guidance throughout the journey and for always making me believe that I can.
- In particular, Jon McCosh (INR), Isabella Gosetto (JNCC), and Dr Thabo Makhubedu (INR) for their unwavering support that I do not think I would complete without.
- The Soil Science family for always remaining intact and supportive anytime when needed.
- My family, particularly my sister, Slindile Shandu and the old man (uMkhulu) for always believing in me even at the times I do not.
- Dr Maseko, Cresswell Mseleku, Dr Ngcobo, Sbonelo Ngubane, Sihle Mayisela, Xola Phiri, Lungelo Majola, Siphokuhle Mbuyisa, Thalent Mbonambi, Mlungisi Mnyandu, Sbonakaliso Zwane, and Sphiwe Mkhize, your contributions, either directly or indirectly, were noticed and highly appreciated.

"I dedicate this dissertation to my late mother and grandmother, uMaNala noMaMthembu. May their souls rest well and continue to provide light and protection. Your efforts never went to waste, you raised a warrior!"

SUMMARY

Inadequate waste collection services in some South African communities have led to indiscriminate disposal of soiled disposable nappies (SDN). This, along with extensive soil degradation, invasive *Acacia mearnsii* encroachment, and livestock fodder shortages, poses environmental and agricultural challenges. This study aimed to evaluate the potential of entrenchment of soiled nappies and biochar derived from *A. mearnsii* wood, to improve, Napier grass (*Pennisetum purpureum*) growth, and fertility of a degraded soil in the Upper uMkhomazi Catchment. The field trial was laid out in a randomized complete block design (RCBD) consisting of seven treatments: control (CON), nappies only (NO), biochar only (BO), nappies + biochar (NB), nappies + fertilizer (NF), fertilizer + biochar (FB), and nappies + fertilizer + biochar (NFB). Napier grass physiological parameters dry matter yield, biomass nutritional value, soil moisture, selected soil fertility factors and microbial biomass carbon (MBC) were measured.

Treatments with nappies greatly enhance Napier biomass yield (up to 5.83 tons ha^{-1}) and macronutrient uptake (N, P, K, Ca, Mg) relative to the control. The uptake of macronutrient was significantly enhanced when the SDN were co-applied with either fertilizer and/or biochar, with the NFB treatment exhibiting the strongest effects on soil fertility and microbial biomass carbon (MBC). However, nappy treatments reduced moisture of soil in the vicinity of the nappies (nappies became a moisture reservoir) compared with the negative control (CON) and BO. Despite improved fertility, nappy treatments did not significantly enhance Napier grass nutritional content. The NFB-amended soils showed enhanced levels of soil nitrogen and manganese compared to the control (CON) and calcium relative to the BO treatment, whereas potassium concentrations were lower than those observed in the NO, NF, and NB treatments. The outcomes of the present study imply that soiled nappies, combined with biochar and fertilizer, offer an approach to manage the waste, rehabilitate degraded soils, boost fertility and moisture storage, which improve crop productivity, especially under dry conditions.

Key words: Calcium, micronutrients, nitrogen, potassium, superabsorbent polymers

TABLE OF CONTENTS

DECLARATION 1 - PLAGIARISM 2

ACKNOWLEDGEMENTS 2

SUMMARY 4

LIST OF FIGURES 8

LIST OF TABLES 10

CHAPTER 1 1

1.1 Background 1

1.2 Rationale 2

1.3 Problem statement 3

1.4 Research questions 3

1.5 Aim and objectives 3

1.6 Hypotheses 3

CHAPTER 2 4

2.1 Introduction 4

2.1.1 Global and national use of disposable nappies 5

2.1.2 Types of disposable diapers 5

2.1.3 Disposal techniques and their environmental impacts 7

2.2 Soil Degradation Extent: Global and Local Scale 12

2.2.1 Global soil degradation 14

2.3 *Acacia mearnsii* De Wild. Encroachment: Ecological Impacts 18

2.3.1 Overview 18

2.3.2 Ecological impacts 19

2.3.3 Management strategies and challenges 20

2.3.4 Wood-based biochar and its agricultural benefits 23

2.4 Napier Grass Production: An Alternative Approach 25

2.5 Integration and Interactions 27

2.6 Conclusions and Future Directions 28

CHAPTER 3 29

3.1 Introduction 29

3.2 Methods and materials 31

***3.2.1* Site description** 31

3.2.2 Soil sampling 32

3.2.3 Land preparation and source of planting material 33

3.2.4 Experimental design, soil amendments and plant propagation 34

3.2.5 Monitoring and data collection 35

3.2.6 Statistical analysis 36

3.3 Results 38

3.3.1 Dry matter (DM) yield 38

3.3.2 Napier grass tiller number, heights and SPAD-based chlorophyll content 40

3.3.3 Chemical composition and mineral concentration of Napier grass 46

3.4 Discussion 51

3.5 Conclusion 55

CHAPTER 4 56

4.1 Introduction 56

4.2 Methods and materials 57

4.2.1 Site description, land preparation and materials used in the study 57

4.2.2 Experimental design, application of soil amendments and plant propagation 57

4.2.3 Data collection, soil sampling and laboratory analyses 57

4.2.4 Statistical analysis 60

4.3 Results 61

4.3.1 Soil moisture 61

4.3.2 Soil fertility status 62

4.3.3 Microbial biomass carbon (MBC) 65

4.4 Discussion 65

4.4.1 Soil moisture content 65

4.4.2 Soil fertility indicators 66

4.4.3 Soil microbial biomass carbon (MBC) 68

4.5 Conclusion 68

CHAPTER 5 70

5.1 General Discussion 70

5.2 Limitations, Conclusions and Recommendations 72

REFERENCES 73

LIST OF FIGURES

Figure 2.1: Diagrammatic illustration of a Pampers disposable nappy (Johnson, 2020) 6

Figure 2.2: Common lifecycle of disposable nappies (Mendoza et al., 2019a). 7

Figure 2.3: Diagrammatical sketch of a landfill for municipal solid waste ((EPA), 2024). 8

Figure 2.4: Prospective environmental ramifications of landfilled waste (Vaverková, 2019). .9

Figure 2.5: Various types of soil degradation (Lal, 2015). 14

Figure 2.6: The distribution and severity of soil degradation across the globe (Jie et al., 2002). 16

Figure 2.7: Level of land utilization in Macubeni District, Eastern Cape, South Africa (Sibiya et al., 2023). 18

Figure 2.8: *Acacia mearnsii* invasion and distribution in South Africa (Le Roux et al., 2011). 19

Figure 2.9: Stages of acacia life cycle at which control strategies can be implemented (Wilson et al., 2011). 20

Figure 2.10: The mean number of seeds per square meter in (A) litter, (B) soil, and (C) seed bank in Western Cape, South Africa (Strydom et al., 2017). 21

Figure 2.11: Soil extractable NH_4^+ at (a) mid-growing and (b) end-growing seasons; and soil potentially mineralizable nitrogen (PMN) at (c) mid-growing and (d) end-growing seasons in response to poultry litter, biochar and co-application (Gao et al., 2016).....24

Figure 3.1: Study site locality map. 32

Figure 3.2: Interactive effect of growth cycle x treatment on a) leaf, b) stem and c) total DM yield as influenced by seven treatments.....39

Figure 3.3: SPAD-based chlorophyll content from Napier grass subjected to seven treatments over two growth cycles. 43

Figure 3.4: Relationship between DM yield and (a) tiller height, and (b) tiller count of growth cycle 1 and (c) tiller height and (d) count of growth cycle 2 at harvesting period. 45

Figure 3.5: Interactive effect of growth cycle x treatment on crude protein of Napier grass. Lowercase letters denote significant differences between treatments at $p \leq 0.05$. 47

Figure 3.6: Napier grass (a) nitrogen (N) and (b) calcium (Ca) uptake in response to seven treatments and two growth cycles. 49

Figure 4.1: Volumetric water content monitored using HS2 device coupled with CS658 probes at (a) 10cm and (b) 20cm depths as affected by seven treatments.....61

Figure 4.2: Average moisture content recorded from inside the entrenched SDN. 62

Figure 4.3: A significant response of (a) total N, (b) exchangeable K, (c) exchangeable Ca, and (d) available Mn to seven treatments according to Tukey's LSD 63

Figure 4.4: Microbial biomass carbon as affected by seven treatments at 0-20cm. 65

LIST OF TABLES

Table 2.1: Properties of composts with and without nappies (modified from Espinosa-Valdemar et al., 2014).....11

Table 2.2: Global and continental estimates of soil degradation extent from different sources (in million hectares). Modified from (Gibbs and Salmon, 2015) 14

Table 2.3: Nutrient composition of selected Napier grass cultivars (Turano et al., 2016). 27

Table 3.1: Topsoil (0-30cm) fertility status of the experimental site prior to planting.....33

Table 3.2: A two-way ANOVA of leaf, stem and total dry matter (DM) yield of Napier grass following ap-plication of seven treatments and two growth cycles.....38

Table 3.3: A 2-way ANOVA for tiller height, number and SPAD-based chlorophyll content of Napier grass as affected by seven treatments. 42

Table 3.4: A two-way ANOVA for a nutritional value in Napier shoots subjected to seven (7) different treatments. 46

Table 3.5: A two-way ANOVA for macronutrient uptake in Napier grass shoots subjected to seven (7) different treatments. 48

Table 3.6: A 2-Way ANOVA of micronutrient concentrations in Napier grass as influenced by seven treatments.....50

Table 4.1: Selected soil fertility indicators in response to seven treatments at 30cm below soil surface.....64

CHAPTER 1

General Introduction

1.1 Background

Effective management of solid waste (SW) has emerged as a pressing worldwide issue due to its significant threats to human health and the environment (Albanna, 2012). Soiled disposable nappies (SDN) form a substantial component of municipal solid waste (MSW) owing to extensive use and unsustainable disposal approaches. Disposable nappies provide convenience for modern society due to their ease of use, affordability and effectiveness in excreta containment (Kakonke et al., 2019). However, the poor waste management options, negates the benefits of these nappies, which often end up in landfills or improperly disposed, particularly in rural and peri-urban regions. Nappy waste, particularly the indiscriminately disposed, contributes to soil, air and water pollution, threatening public health and the environment (Ntekpe et al., 2019). South Africa lacks efficient solid waste management systems in rural and peri-urban areas, which have no municipal disposal collection services. In 2020, South Africa generated more than 31 million tons of SDN waste (Khanyile et al., 2020), which was dumped in mismanaged landfills and hugely indiscriminately disposed. This waste management challenge is compounded by other challenges in these areas, including soil degradation and low crop and fodder productivity.

Rural communities in South Africa (SA) heavily rely on subsistence farming for food security and economic stability (Rankoana, 2022) but normally encounter low productivity due to soil degradation. In South Africa, more than 30% of soils are sandy, while about 60% of soils are poor in organic matter content and therefore accelerate soil degradation (Msangi, 2007). Soil degradation is intensified in poverty-stricken areas of SA, due to unsustainable agricultural practices, such as monoculture coupled with intensive tillage (Mani et al., 2021). Dlamini et al. (2014) reported that water-induced soil removal, nutrient leaching, and decline in vegetation were among the factors to cause soil organic carbon (SOC) and nitrogen (N) pool losses in South African soils. The upper uMkhomazi catchment in South African has over 7500 ha of abandoned communal lands due to soil degradation (DEA, 2018). In addition to enduring soil degradation, the grasslands in the upper uMkhomazi region experiences encroachment of black

wattle (*Acacia mearnsii*), listed in the top 100 of the global worst invasive species (Poudel et al., 2024). This results to decline in agricultural production and impacts fodder availability for local farmers. The of SDN waste, soil degradation, *A. mearnsii* encroachment and livestock fodder shortages therefore impact human livelihoods.

1.2 Rationale

The SDNs, although regarded as waste contain faecal matter and urine which are abundant in essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K) that are crucial for soil productivity and crop growth (Kutu et al., 2011). The organic component of SDNs could also contribute to organic matter accumulation, enhance microbial communities, improve nutrient balance through cycling and mineralization, and the overall soil quality (Brock et al., 2017). Superabsorbent polymers (SAPs), a key constituent of disposable nappies capable of absorbing moisture up to 100-fold their own weight, exhibit efficacy in retaining soil moisture (Bachra et al., 2020). Sánchez-Orozco et al. (2017) studied the applicability of SAPs in soil and agriculture and reported improved moisture retention and enhanced agricultural productivity. These benefits present an opportunity to use nappies to improve degraded soils. Encroachment of grasslands with the invasive species*, A. mearnsii*, is detrimental to agriculture and livestock fodder availability in the area.

There is also emerging attention in wood-derived biochar for improving productivity of poor quality soils, through its effectiveness on carbon sequestration, pH regulation, nutrient and moisture retention, and prevention of soil erosion (Manirakiza et al., 2024). Therefore, deriving biochar from the invasive black wattle wood could provide the environment with aforementioned benefits, particularly degraded soils, and address encroachment with the invasive species that takes over communal lands. Napier grass, an efficient, robust, high yielding fodder crop, that also resists unfavourable environmental conditions (Waramit and Chaugool, 2014), could be ideal for producing animal feed on degraded soils. In addition to potential provision of livestock fodder, Napier grass has been observed to improve soil fertility and hydrological properties (Yang et al., 2016). While the effects of sole applications of SAPs and *A. mearnsii* biochar in agriculture have been studied, the impact of their co-application on the production of Napier grass on degraded soils remain unexplored. Entrenching SDN and *A. mearnsii biochar* presents a novel opportunity to tackle the pressing concerns of SDN waste

and black wattle invasion, while producing Napier grass, increasing the productivity of degraded soils.

1.3 Problem statement

The SDNs are indiscriminately disposed of due to lack of municipal refuse collection systems in many areas in South Africa. Communal areas in the upper uMkhomazi catchment face the challenges of soil degradation and invasion by the invasive *A. mearnsii*. These issues threaten food security and fodder availability for local farmers. Entrenchment of nappies and biochar from *A. mearnsii* as soil amendments for production of animal fodder, could sustainably tackle the challenges of improper SDN disposal, black wattle invasion and reverse soil degradation, and livestock fodder shortages.

1.4 Research questions

- What effect will SDN and biochar applied as soil amendments have soil moisture and soil chemical and biological parameters?
- What influence will SDN and black wattle biochar have on Napier grass growth and dry matter accumulation?

1.5 Aim and objectives

This study aimed to examine the effects of entrenching SDN and black wattle (*Acacia mearnsii*) biochar on Napier grass growth, dry matter accumulation, soil moisture, and fertility. The specific objectives were:

- To determine the effects of entrenchment of soiled disposable diapers and *A. mearnsii* biochar on Napier grass physiological parameters and dry matter (DM) yield.
- To determine the effects of entrenchment of SDN and *A. mearnsii* biochar on soil moisture, selected soil fertility parameters and microbial biomass carbon.

1.6 Hypotheses

- The entrenchment of SDN and black wattle biochar enhances Napier grass growth and dry matter accumulation.

- SDN and *A. mearnsii* biochar as soil amendments improve soil moisture content, fertility parameters, and microbial biomass carbon.

CHAPTER 2

Environmental Implications of Soiled Nappies, Soil Degradation, and *A. mearnsii*: A Review with Emphasis on Prospective Applications in Napier Fodder Production

2.1 Introduction

The extensive use of disposable nappies has resulted to substantial environmental concerns, primarily due to their slow decomposition, hazardous chemical composition, and high volumes of waste generation (Mendoza et al., 2019b). Common disposable nappies are composed of plastics, synthetic fibres, and absorbent polymers, which substantially slows down degradation in landfills, resulting in adverse environmental and health consequences (Ntekpe et al., 2020). The projected population growth suggests that the demand for and reliance on disposable nappies will likely intensify. Land degradation aggravates this concern since unsustainable agricultural practices, soil removal, and nutrient depletion further deteriorate the environment (Zia-ur-Rehman et al., 2016). Degraded soils are attributed to low fertility, poor moisture regulation, and susceptibility to erosion; hence intervention efforts are urgently required. Furthermore, the proliferation of invasive species, such as *Acacia mearnsii*, accelerates these issues by outcompeting native vegetation, altering soil properties, and diminishing biodiversity (Shiddiq et al., 2023, Lusizi et al., 2024). The encroachment of black wattle on degraded lands exacerbates soil degradation, hindering land use options for agricultural productivity and rehabilitation. Individually, SDN waste, soil degradation, and encroachment of invasive species pose a significant threat to the ecosystem and livelihoods. Their interaction creates a more complex multifaceted environmental detriment that complicates intervention efforts. Addressing these challenges requires an integrated approach that tackles waste concern, induce soil restoration and control invasive species.

2.1.1 Global and national use of disposable nappies

Though disposable nappies are convenient and hygienic, the benefits are often concealed by their ruinous effect to the environment (Kim and Kim, 2018). It is estimated that globally, 134 million babies are born annually, and each baby remains on disposable nappies for about 24 months (Thaman and Eichenfield, 2014). This indicates a considerable dependence on and utilization of disposable nappies. Over 95% of the European Union (EU) utilize disposable nappies and generates about 40 000 units of SDN every minute that largely culminate in landfills (Mendoza et al., 2019b). In the Western region, disposable nappies are a prevalent choice, and recent technologies have improved the quality of nappies, but sustainable disposal remains a concern (Odio and Thaman, 2014). The Sub-Saharan Africa also experience over 95% usage of disposable nappies, but the waste issues are predominant due to lack of infrastructure and waste collection services in most areas (Mudau et al., 2023). South Africa solely produces over a staggering one million tons of SDN annually (Khanyile et al., 2020). The unsustainable disposal of these items exacerbates global environmental degradation through plastic pollution and release of harmful substances.

2.1.2 Types of disposable diapers

Diapers are manufactured in various types to meet certain requirements and preferences, at various times. These include disposable, reusable cloth, biodegradable and hybrid diapers (Khoo et al., 2019).

2.1.2.1 Disposable diapers

SDN are originally generated by households, childcare centres, healthcare facilities or other centres caring for personnel with continence complications (Kimani et al., 2015). The structure of a modern disposable diaper is shown in Figure 2.1. Urine first passes through the top-sheet, a protective layer treated with lotion to prevent skin irritation (Johnson, 2020), before it moves through the absorption layer, made of polyester fibres, which helps transport moisture away from the skin (Mirabella et al., 2013). The absorbent core, containing super-absorbent polymers (SAP) locks in liquid waste and can retain up to 100-fold its weight (Bachra et al., 2020; Xu et al., 2024). The back-sheet, made of breathable film and soft fibers, prevents leaks (Mirabella et al., 2013), while the fastening system, including tapes and hooks, secures the diaper

(Mendoza et al., 2019a, 2019b). Additional features such as inner cuffs, elastics, and wetness indicators enhance comfort and fit (Sen et al., 2019).

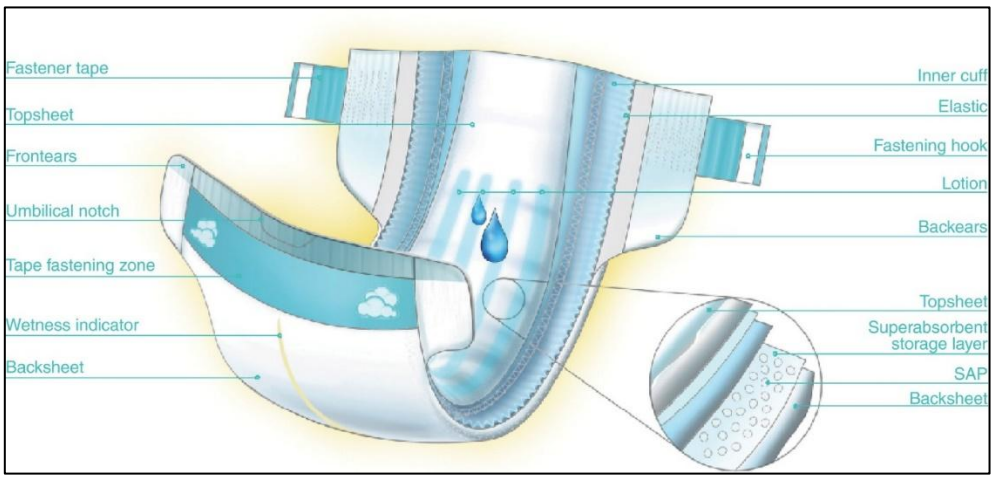


Figure 2.1: Diagrammatic illustration of a Pampers disposable nappy (Johnson, 2020)

Plastic materials like polyethylene and polypropylene constitute about 20% of diaper components, while superabsorbent and fluff pulp accounts for over 25 and 40%, respectively. Fluff pulp, primarily derived from wood pulp via the kraft process, provides high absorption due to its cellulose content (Ismaeilimoghadam et al., 2022; Barros et al., 2022). In regions with limited forestry, sugarcane bagasse is used as a cost-effective alternative, though it has lower absorption capacity and quality (Indumathi and Divya, 2021; Ismaeilimoghadam et al., 2022). SAP, particularly sodium polyacrylate, enhance moisture retention by forming a gel that locks in liquid, working alongside fluff pulp to channel and store fluids (Xu et al., 2024; Castrillon et al., 2019).

2.1.2.2 Biodegradable nappies

Biodegradable nappies are single-use but made from more eco-friendly materials than traditional disposable nappies. They exclude chlorine, dyes, latex, and fragrances in their components, replacing toxic inserts with compost-friendly cotton and using a biodegradable polyurethane laminate (PUL) back sheet instead of polyethylene (Spurrier and Buck, 2015; Zuraida, 2023).

In tests, green nappies demonstrated superior absorbency and comfort, making them a better choice for both performance and environmental impact (Spurrier and Buck, 2015). However, most nappies marketed as *"biodegradable"* still contain plastics and chemicals, and real biodegradation only occurs under commercial composting conditions (Hirsh, 2022). While biodegradable nappies decompose ten times faster than conventional ones, reducing landfill lifespan from 500 to 50 years, they still release greenhouse gases and persist in natural environments like traditional disposable nappies (Hirsh, 2022).

2.1.3 Disposal techniques and their environmental impacts

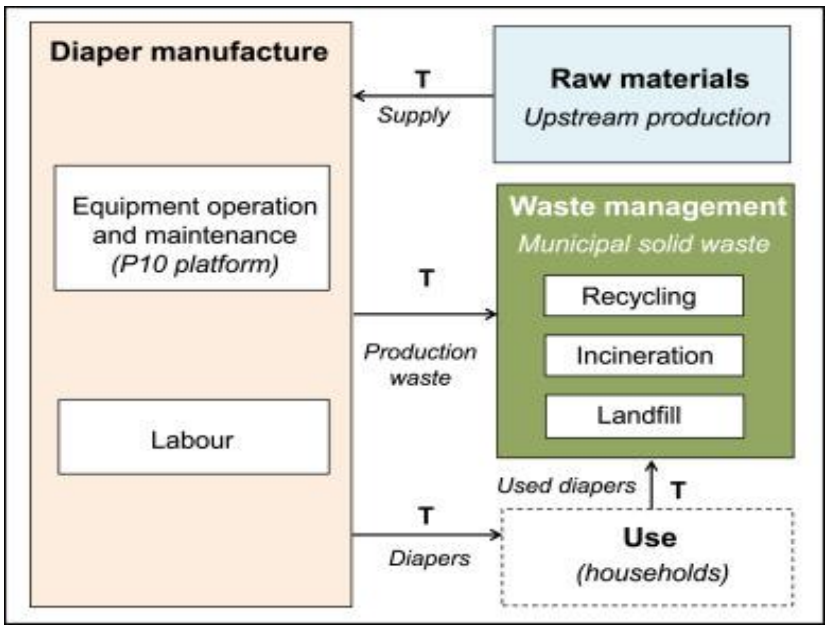


Figure 2.2: Common lifecycle of disposable nappies (Mendoza et al., 2019a).

The approaches to managing SDN waste differ across regions in response to various socioeconomic factors such as economic resources, public awareness and education, access to public services, regulatory framework, etc. The SDN waste commonly ends up in landfills, incineration, recycling, and free dumping (**Figure 2.2**) (Mendoza et al., 2019a).

2.1.3.1 Landfilling

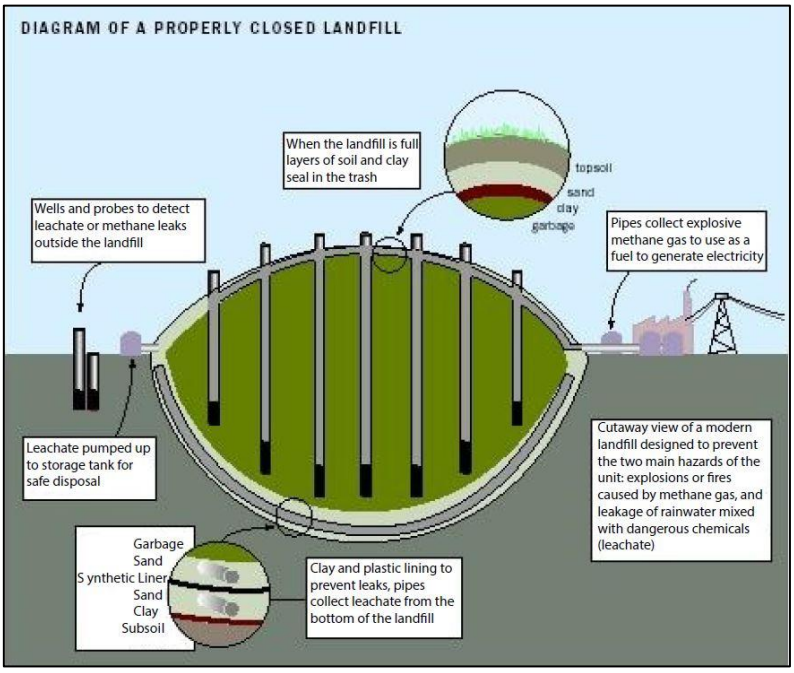


Figure 2.3: Diagrammatical sketch of a landfill for municipal solid waste ((EPA), 2024).

Landfilling is commonly adopted in managing disposable nappy waste. Landfilling refers to a waste management technique where solid waste, along with soiled nappies is collected to be disposed into a landfill system as shown in **Figure 2.3**. With sophistication in modern landfills, waste is deposited, compacted and covered with soil. Underneath, there is a system designed to minimize environmental ramifications by collecting leachate from waste to be treated of contaminations (Teng et al., 2021). Landfills are also designed to restrict waste from association with underground environment, soil and/or water (Huo et al., 2022). Landfilling is preferred over other waste disposal methods due to its economic benefits (Renou et al., 2008). Landfills can be low-cost, convenient and allow waste to undergo complete end-of-life processes in a controlled environment (Renou et al., 2008, Vaverková, 2019). Whilst it appears to be a solution, it draws waste away from human sight but unsustainably buries it into the soil. The lack of effective landfilled-waste treatment keeps it for extended periods of time. A disposable diaper waste is estimated to take about 500 years to be completely decomposed. A piece of land operating as a landfill site then stays occupied by nappies for at least five centuries, which is incredibly lengthy. This limitation is detrimental to sustainability as solid

waste, including nappies, are characterized by slow decomposition (Parker, 2021). Vaverková (2019) found that anaerobic landfill systems were responsible for the release of gases composed of 40-60% methane, causing air pollution and ozone depletion (Parker, 2021).

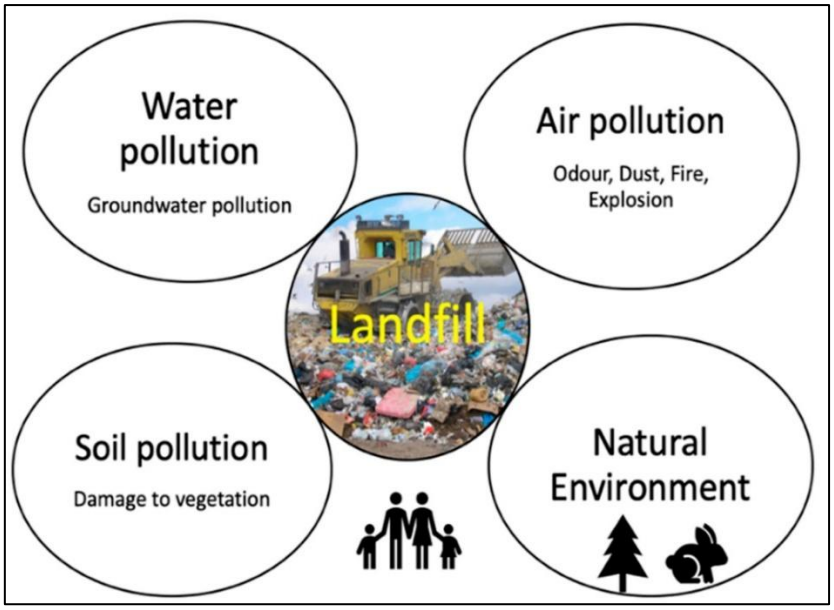


Figure 2.4: Prospective environmental ramifications of landfilled waste (Vaverková, 2019).

Landfilled waste can also contaminate soil, groundwater and cause loss of biodiversity loss as summarized in **Figure 2.4**. Hoffmann et al. (2020) also reported a catastrophic impact of disposable nappies landfilled in both sanitary and unsanitary landfills on climate change and human health on account of greenhouse gas (GHG) emissions.

2.1.3.2 Incineration

Incineration involves the thermal treatment of waste through combustion at high temperatures of around 950ºC and dramatically reduce volumes into ash, gases and heat (Khoo et al., 2019). Incineration originated as a solution to tackle hazardous waste issues. Disposable nappy waste incineration (DNWI) occurs at high temperatures due to the moisture content in nappies. Incineration effectively reduces waste volume and weight while also destroying pathogens like *E. coli* (Cheng et al., 2017). Additionally, it can generate energy, producing up to 47 MJ of steam and 16 MJ of electricity (Gould, 2014; Ntekpe et al., 2019). However, DNWI is linked to air pollution, emitting GHG, dioxins, furans, and heavy metals, which harm ecosystems and

public health (Khoo et al., 2019; Lee et al., 2015). While incinerators claim to mitigate these risks, the environmental impact remains a concern (Gould, 2014).

2.1.3.3 Recycling

Recycling of SDN waste involves complex processes of recovering and repurposing organic and inorganic components of nappies to produce materials reusable products (Siregar, 2022). Mechanical recycling targets the non-biodegradable component of nappies such as plastics and SAP to produce reusable materials. A closed-loop system, though not common, is a form of mechanical recycling that is associated with reclaiming nappy components for production of new nappies or other absorbent hygiene products (AHP) (Itsubo et al., 2020). A new technology developed by Itsubo et al. (2020) successfully reclaimed SAP and pulp from SDN, with the aim to restore and match the primary for potential reuse. Open-loop recycling involves repurposing nappy components into diverse products other than those related to nappies. Lim et al. (2022) highlighted that nappy constituents can be repurposed into lithium-ion battery anodes, energy pellets (to generate power), soil amendments, concrete mixtures and substrates for growing mushrooms. Wresta et al. (2024) produced hydrochar, from SDN waste by hydrothermal carbonization (HTC) method. This process heated the shredded nappies between 200 – 250^{o}C for up to 45 minutes, resulting to hydrochar that has various applications including fuel, soil amendment, wastewater treatment (WWT) and carbon sequestration (Islam et al., 2022, Masoumi et al., 2021, Wresta et al., 2024).

Leurs (2021) postulated that recycling of SDN waste can release 37% less GHG than incineration. However, this process is ascribed to limitations such as the incapabilities of existing systems to overcome the intricate composition of nappies for efficient recycling (Wresta et al., 2024). In closed-loop systems, the reclaimed products are commonly inferior to be utilized in re-manufacturing (Leurs, 2021). The high costs and lack of public awareness about the proper process and infrastructure of recycling further negate this strategy (Lim et al., 2022, Wresta et al., 2024). All these limitations hinder extensive adoption of recycling, despite the reported environmental benefits.

2.1.3.4 Composting

Another SDN waste management technique gaining interest is the incorporation into composting systems. Explored by Espinosa-Valdemar et al. (2014), SDN containing urine were integrated into compost with yard waste and produced compost that met the Mexican regulatory standards, except for pH that was slightly higher (**Table 2.1**). Additionally, nappy weight was reduced by more than 85%, signifying degradation of nappy components. Interestingly, though within the limit, faecal coliforms in nappy-inclusive compost were less than in non-nappy-inclusive compost. This underscores successful pathogen removal during the composting process (Espinosa-Valdemar et al., 2014). Though the technique appears to be eco-friendly, it is also limited by the complexity of nappy composition and costs.

Table 2.1: Properties of composts with and without nappies (modified from Espinosa-Valdemar et al., 2014)

Parameter	Without nappies	With nappies	Local* standard PROY-NADF-020-AMBT-2011
Humidity (%)	48.28 ± 5.6	42.40 ± 4.2	25–45
pH (1:9 extract)	8.66 ± 0.05	8.31 ± 0.09	6.5–8
Organic matter (%)	66.28 ± 7.8	67.42 ± 1.5	>20
Nitrogen (%)	3.74 ± 0.23	3.54 ± 0.04	1–4
C/N	10.28 ± 0.55	11.06 ± 0.37	<15
Faecal coliforms	590 ± 226	165 ± 190	<1000 MPN/g

*Mexican disposable nappy regulation standard

2.1.3.5 Free dumping

Free dumping is a widely adopted waste management method, practiced by over 90% of rural and 60% of peri-urban residents worldwide (White et al., 2023). This behaviour is largely attributed to limited environmental awareness among low- to middle-income households (Mbokazi and Lebeloane, 2024), has significant environmental and health implications. For example, in Dukuduku village, KwaZulu-Natal province, South Africa, high volumes of SDN are indiscriminately dumped, often near water streams, increasing pathogen exposure risks for humans and animals (Mbokazi and Lebeloane, 2024). An investigation in the Kruger to

Canyons (K2C) region revealed 433 unauthorized waste disposal sites, with over 75% near water bodies, posing serious contamination threats and contributing to microplastic pollution from nappy degradation (Nell et al., 2024). Furthermore, the practice of "Jay-dumping"—disposing of waste in isolated locations—hinders waste recovery, exacerbates environmental burdens, and compromises sanitation (White et al., 2023; Thomas-Possee et al., 2024). Addressing this issue aligns with SDG Target 6.2 on hygiene and sanitation, underscoring the urgency for sustainable waste management innovations (Thomas-Possee et al., 2024).

2.1.3.6 Agricultural application of human waste

The entrenchment of SDN as soil amendments in agriculture remains generally uncharted, with limited to no scientific literature available. To address this gap, this section reviews the agricultural application of sewage sludge (SS), which serves as a relevant alternative due to its similar composition—both SS and SDNs are rich in organic matter and essential nutrients. As a by-product of municipal wastewater treatment, SS is a nutrient-rich resource, containing vital macro- and micronutrients such as nitrogen (N), phosphorus (P), and potassium (K) (Usman et al., 2012). Its application in agriculture is becoming prevalent as a sustainable disposal method that supplies nutrients (Usman et al., 2012). A field study investigating decade-long application of SS amendment contrasted with inorganic fertilization on maize cultivation revealed that SS-treated soils accumulated sufficient nutrients. These nutrients were abundant enough to substitute P and micronutrient fertilization, without compromising maize yields (Melo et al., 2018). SS has been espoused to prospectively reclaim degraded soils. Hoffmann et al. (2024) postulated that SS increased SOC and total N following application in degraded. Moreover, the treatment effects were apparent even a year after application. This demonstrated the potential of SS to restore degraded soils, but also as a potentially long-term amendment. With careful management, the entrenchment of SDN could also benefit the crop, soil and the environment.

2.2 Soil Degradation Extent: Global and Local Scale

Soil degradation compromises agricultural productivity and biodiversity by reducing soil quality and its capacity to sustain life (Aulakh and Sidhu, 2015). It is driven by both natural and anthropogenic mechanisms, such as soil erosion, nutrient depletion, acidification, organic matter loss, and salinization (Zia-ur-Rehman et al., 2016). Globally, over 1.2 billion hectares of land—22% of agricultural land—is degraded, particularly in low-income regions like parts

of Asia and Sub-Saharan Africa (Bekuzarova et al., 2020). Natural causes, such as wind or water erosion, reduce soil productivity by removing fertile topsoil (Endale et al., 2023). Human-induced drivers include unsustainable agricultural practices like monoculture, overgrazing, and excessive reliance on synthetic fertilizers (Agim et al., 2022; Endale et al., 2023). Deforestation further exacerbates degradation by disturbing soil structure and causing organic matter decline (Endale et al., 2023).

South Africa faces significant soil degradation, especially in rural areas, due to land-use changes, overgrazing, and erratic climate conditions. These challenges negatively impact food security and livelihoods (Tully et al., 2015; Ebhuoma et al., 2023; Kgaphola et al., 2023). Understanding the local and global drivers of soil degradation is vital for implementing effective, area-specific mitigation strategies. There are various types of soil degradation as shown in (**Figure 2.5).**

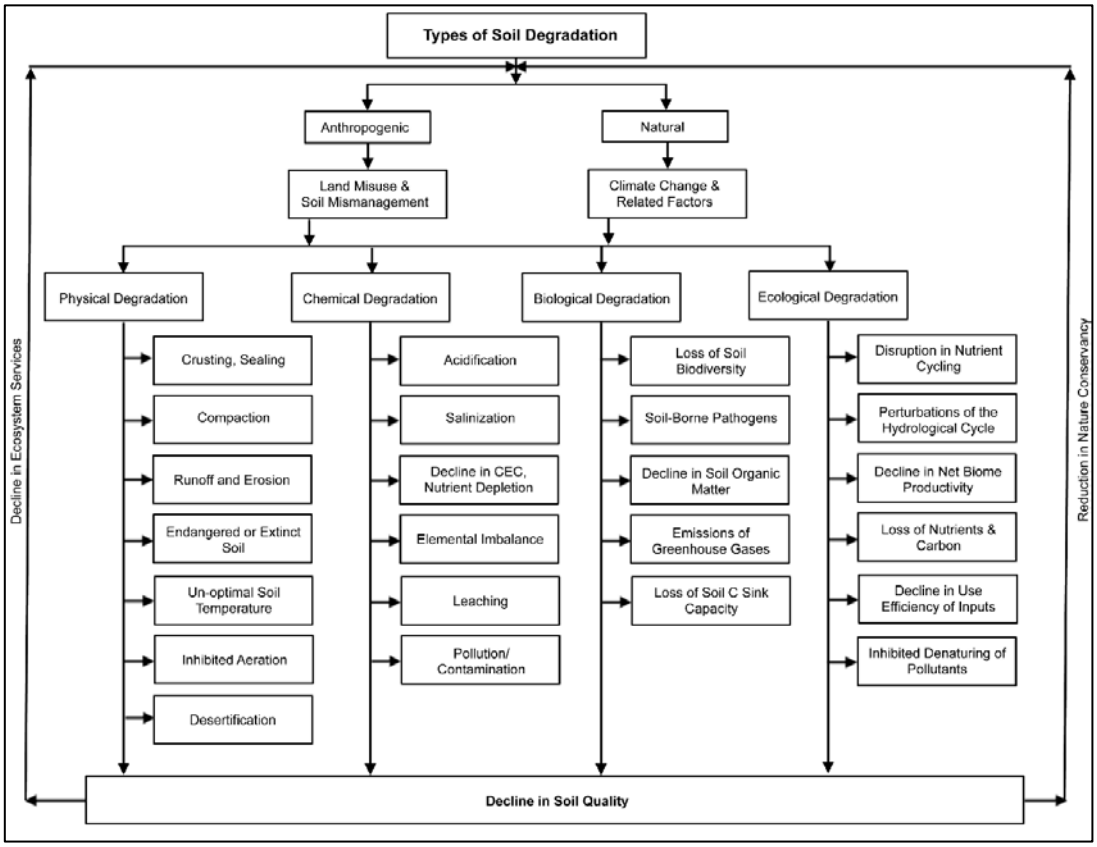


Figure 2.5: Various types of soil degradation (Lal, 2015).

2.2.1 Global soil degradation

Table 2.2: Global and continental estimates of soil degradation extent from different sources (in million hectares). Modified from (Gibbs and Salmon, 2015)

Area	Source						
	GLASOD	FAO TerraSTAT	Dregne &Chou (1992)	GLADA	Cai et al. (2008)	Campbell et al. (2008)	FAO Pan-tropical Landsat
Africa	321	1222	1046	660	132	69	9
Asia	453	2501	1342	912	490	118	12
Australia &Pacific	6	368	376	236	13	74	[d]
Europe	158	403	94	65	104	60	[d]
N America	140	796	429[a]	469	96	79	[d]
S America	139	851	306b	398	156	69	56[b]
Global	1216	6140	3592	2740	991	470	76[d]

[a] Excludes the Caribbean [b] Involves select Caribbean countries [c] Total area calculated based on country data from Table 2 of Bai et al. (2008), which differs from the global total reported in the same source (3506 million ha) [d] Non-tropical continents are not included in this analysis

Soil degradation, a global challenge threatening agriculture and biodiversity, is driven by soil erosion, vegetation decline, land use changes, climate change, and soil pollution (Borrelli et al., 2017; Jie et al., 2002). Gibbs and Salmon (2015) evaluated land degradation using a combination of expert opinions, satellite-derived net primary productivity (NPP), biophysical models, and abandoned cropland mapping. These methods consistently identify Africa, Asia, and South America as the most severely impacted continents, with 300 million hectares of soils classified as severely degraded (Jie et al., 2002) (Table 2.2).

Soil degradation is driven by interconnected factors, including soil and water erosion, salinization, and acidification. Erosion depletes fertile topsoil, reducing productivity and biodiversity (Nachshon, 2020). Salinization and acidification, by altering soil pH, reduce nutrient availability, further hindering soil productivity (Naz et al., 2022). Vegetation decline, caused by deforestation and overgrazing, exacerbates soil erosion and loss of organic matter, structure, and fertility (Borrelli et al., 2017; Prăvălie et al., 2021). These factors collectively impact global agriculture and livelihoods, highlighting the need for interventions.

The drivers of soil degradation are interconnected. Nachshon (2020) contends that global soil degradation is largely demonstrated through soil and water erosion that erode the fertile topsoil, hindering the soil's ability to sustain life. Salinization and acidification also degrade soils (Borrelli et al., 2017, Nachshon, 2020) because nutrient solubility and availability relies substantially on soil pH. Highly saline soils tend to decrease the soil pH, reducing the availability of nutrients and thus declining the soil productivity (Naz et al., 2022), a similar effect with acidification. Vegetation decline, a major driver of soil degradation, increases erosion risk by removing stabilizing roots and soil cover (Prăvălie et al., 2021). A decline in plant cover can be exacerbated by deforestation or overgrazing, subjecting the soil to losses in organic matter, structure and fertility (Borrelli et al., 2017). Soil degradation impacts, even at a global level, extend from agriculture over to livelihoods and require interventions.

Degraded soils can be restored by soil quality enhancing methods. Restoration of degraded soils involves techniques such as conservation agriculture (CA), retaining vegetation cover, controlled grazing, and crop rotation (Lal, 2015; Agim et al., 2022). Restorative techniques such as CA, retention of vegetation as soil cover, and controlled grazing can enhance soil quality, reversing soil degradation (Lal, 2015). Sustainable agricultural practices like crop rotation and conservative tillage can improve soil fertility and contribute to restoration (Agim et al., 2022). Singh et al. (2022) suggested that the application of microbes that supports the formation of glomalin, a protein crucial for soil fertility could be effective in ameliorating soil degradation. Furthermore, cover cropping and addition of organic matter was reported to be capable of remediating degraded soils. Sustainable Development Goal (SDG) 15.3 is a global effort that aims to combat soil degradation by achieving land degradation neutrality (LDN) by 2030 and aligning with such initiative could significantly remediate soil degradation (Feng et al., 2022).

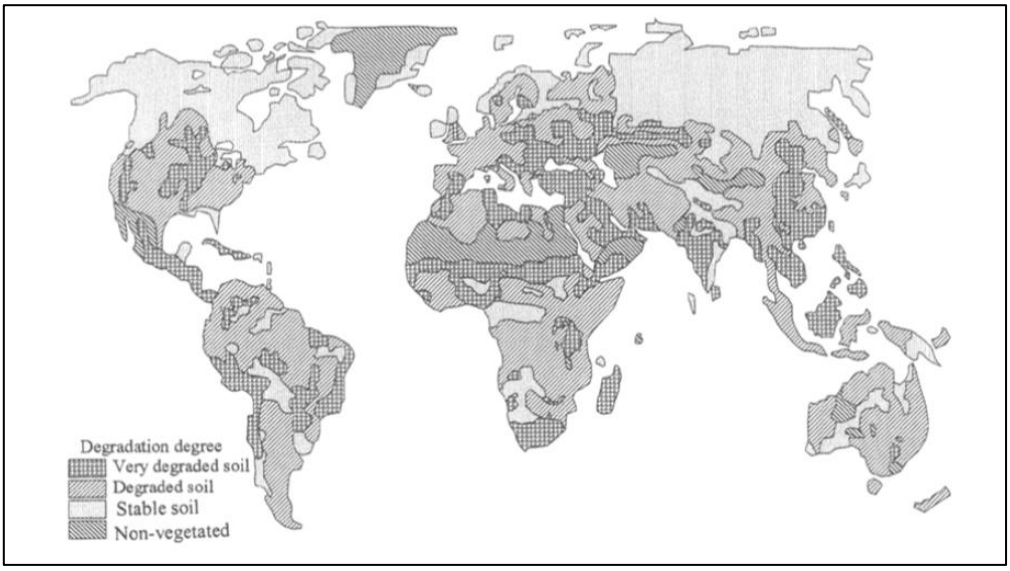


Figure 2.6: The distribution and severity of soil degradation across the globe (Jie et al., 2002).

Local soil degradation case studies

South Africa, a developing country in Africa is one of the severely degraded countries globally. In the Eastern Cape province, particularly Macubeni district, 37% of the mapped area is abandoned, with 20% of it being extremely degraded (Sibiya et al., 2023). About 50% of croplands in the area are degraded, threatening agriculture. Intensive farming and overgrazing were identified as key drivers, exacerbated by poverty and reliance on subsistence farming, which promotes unsustainable practices requiring targeted interventions (Sibiya et al., 2023).

In KwaMaye, KwaZulu-Natal, severe soil erosion has persisted despite control measures like terracing. Contributing factors include overgrazing due to increased livestock populations, erratic climate, and lack of government support (Ebhuoma et al., 2023). Similarly, in the upper uMgeni catchment, unsustainable land use accelerated soil degradation, leading to reduced water quality in reservoirs. Eroded topsoil, rich in nutrients, is deposited into water bodies, causing eutrophication and reduced water quality (Makaya et al., 2019; Issaka and Ashraf, 2017).

In Sekhukhune district, Limpopo, land use changes, such as conversion from dense bush to residential areas and grasslands to bare soil, have exacerbated soil degradation, biodiversity loss, and declining agricultural productivity. A lack of local leadership was identified as a significant barrier to effective control measures (Kgaphola et al., 2023). Soil degradation in South Africa mirrors global trends but is intensified by factors like woody alien species encroachment, overgrazing, and erratic climate (Gbetibouo et al., 2010; Le Roux and Smith, 2014; Manjoro et al., 2012). Impacts range from reduced agricultural productivity to biodiversity loss and food insecurity, necessitating urgent sustainable interventions. Invasive species such as black wattle (*A. mearnsii*) further worsen soil degradation. Current remediation measures include conservation agriculture, phytoremediation, conserved tillage, and controlled grazing (Lal, 2015).

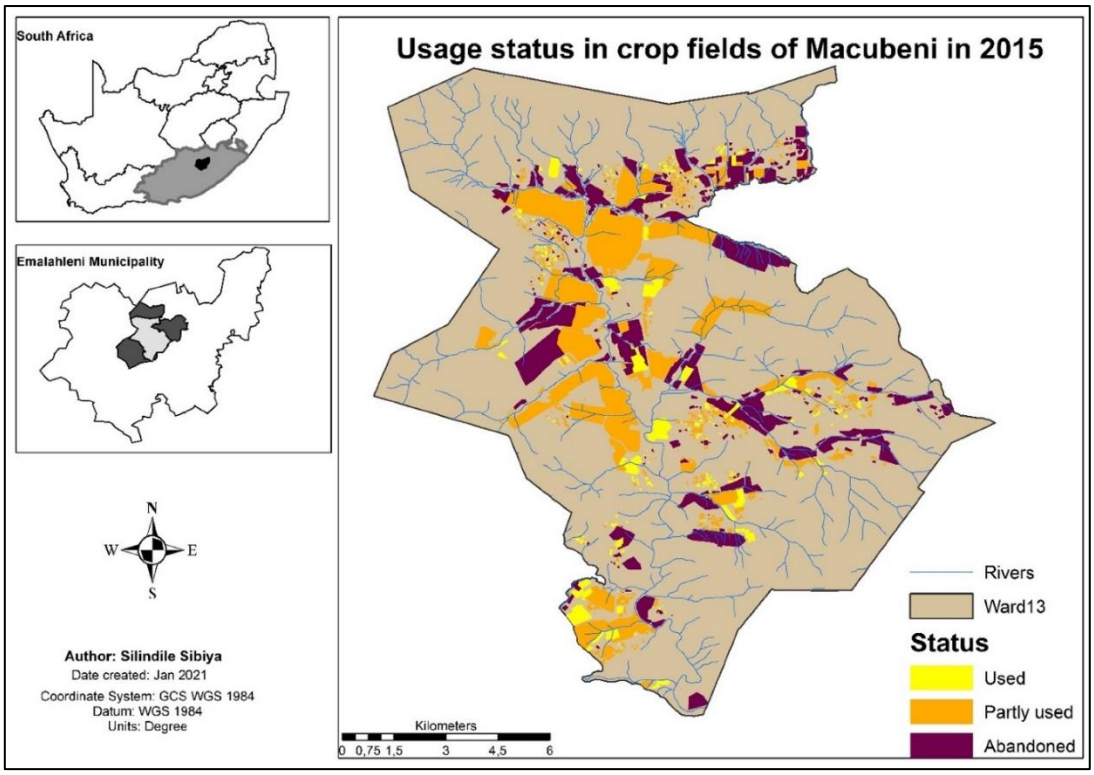


Figure 2.7: Level of land utilization in Macubeni District, Eastern Cape, South Africa (Sibiya et al., 2023).

2.3 *Acacia mearnsii* De Wild. Encroachment: Ecological Impacts

2.3.1 Overview

Most Acacia species, including *Acacia mearnsii* (black wattle), originate from Australia but have become invasive in many regions, particularly in South Africa (Richardson et al., 2023). Initially introduced in 1884 for purposes like livestock shade, windbreaks, and tannin production, *A. mearnsii* has since spread extensively, invading over 2.5 million hectares (Galatowitsch & Richardson, 2005; Govender, 2007).

Black wattle is a fast-growing species, reaching maturity in 7–10 years in monocultures and 3–6 years in mixed plantations (Forrester et al., 2004; Soares et al., 2018). It has a high germination rate of about 95%, thriving across temperate, subtropical, and tropical climates (Dessì et al., 2021; Rojas-Sandoval & Pasiecznik, 2022). Its nitrogen-fixing ability allows it to colonize nutrient-poor soils, contributing to its resilience in degraded areas (Forrester et al.,

2007). Additionally, its symbiotic relationship with endophytic bacteria enhances nutrient uptake and stress tolerance, further strengthening its invasive potential (Rojas-Sandoval & Pasiecznik, 2022; Shiddiq et al., 2023).

2.3.2 Ecological impacts

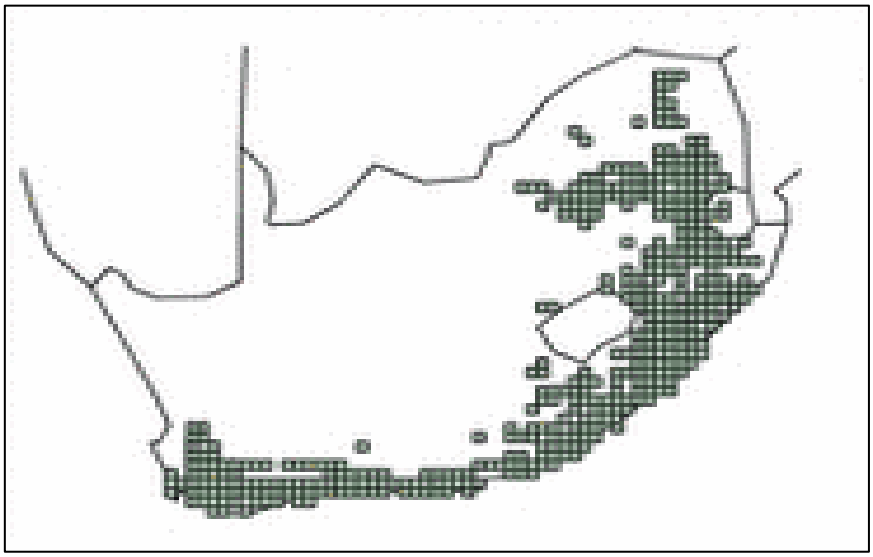


Figure 2.8: *Acacia mearnsii* invasion and distribution in South Africa (Le Roux et al., 2011).

The above diagram (**Figure 2.8**) illustrates dense invasion of *A. mearnsii* in South Africa. The encroachment of *Acacia mearnsii* negatively impacts biodiversity and livelihoods by outcompeting native species for resources, often leading to their displacement. Its significant nitrogen-fixing ability enhances soil nitrogen levels, benefiting its own growth but causing nutrient imbalances that threaten indigenous plants (Shiddiq et al., 2023). In ecosystems with closely related native species, *A. mearnsii* can promote hybridization, altering local genomes and contributing to species decline.

Black wattle invasion also modifies soil properties. Lusizi et al. (2024) noted a decline in soil pH and mineral nitrogen, with increases in other physicochemical attributes, while Ruwanza (2017) observed that only phosphorus decreased following *A. mearnsii* encroachment. Murugan et al. (2020) reported a reduction in soil MBC and enzyme activity after alien species removal. Though some soil changes appear beneficial, they primarily support *A. mearnsii*, reinforcing its invasiveness and complicating control efforts.

2.3.3 Management strategies and challenges

South Africa, like other *Acacia mearnsii*-invaded countries, has a strong focus to control the invasiveness of black wattle. The techniques currently in place to control the invasiveness of *Acacia mearnsii* include mechanical and biological processes, industrial repurposing, and integrated method approaches. The spread of black wattle, similar to any Australian acacias, can be controlled at various stages of growth (**Figure 2.9**). Australian acacias have a similar life cycle and similar control measures can be applied across the species (Wilson et al., 2011)

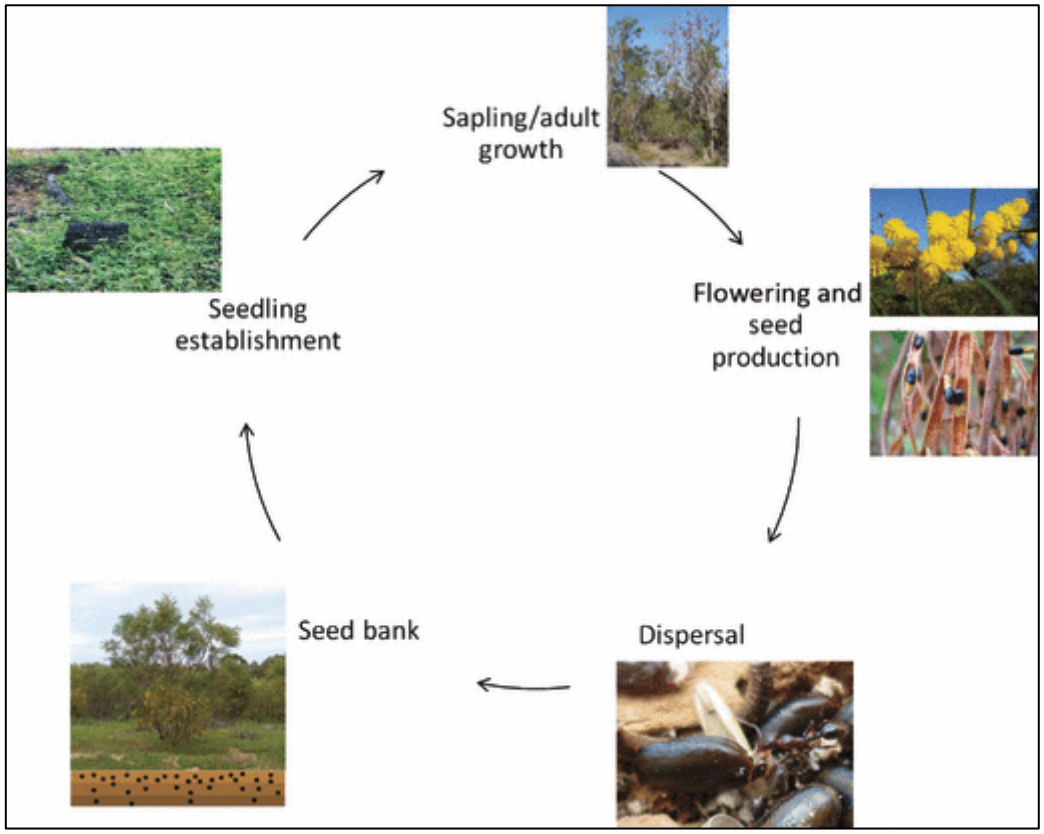


Figure 2.9: Stages of acacia life cycle at which control strategies can be implemented (Wilson et al., 2011).

2.3.3.1 Mechanical techniques

Mechanical control of *Acacia mearnsii* involves cutting trees and removing stumps to prevent regrowth (Rojas-Sandoval and Pasiecznik, 2022). While labour-intensive, this method is effective on a small scale. Machinery-assisted techniques like cut-and-ring barking have been highly successful, particularly for trees larger than 16 cm in diameter and cut at greater heights (Muvengwi et al., 2018). Mechanical removal is typically applied to mature trees, but its main

limitation is the regeneration from the species' extensive soil seed banks, resulting from its high fecundity (Strydom et al., 2017).

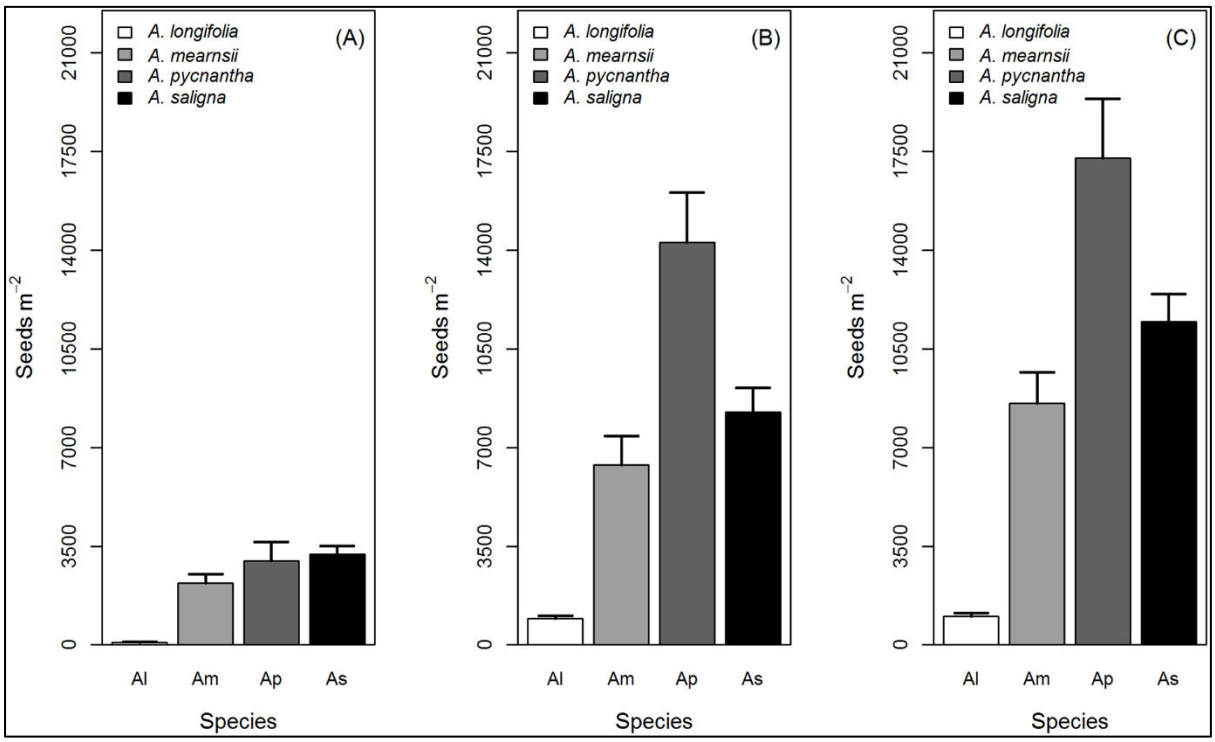


Figure 2.10: The mean number of seeds per square meter in (A) litter, (B) soil, and (C) seed bank in Western Cape, South Africa (Strydom et al., 2017).

As shown in **Figure 2.10**, the seed banks contain the significantly highest number of seeds/m^2. Wilson et al. (2011) highlighted various measures that can be adopted to destruct *A. mearnsii* seed banks that included fire burning, soil disturbance, litter eradication, soil surface covering, topsoil removal and solarization. Except for soil surface covering, where the soil is covered with about 20cm of soil to suppress germination and potential seedlings, these methods promote germination. The idea is that if germination is supported, the number of seeds will decrease from the seed banks and the seedlings can then be removed effectively. Mechanical clearing is significantly more effective than biological control regarding management of seed banks due to immense deposits (Strydom et al., 2017).

2.3.3.2 Biological control

Unlike mechanical control, biological methods target flowers, seeds, and seedlings, preserving commercially valuable parts. This approach involves introducing natural antagonists, such as

insects, fungi, and pathogens, to suppress reproduction and growth. The flower-galling midge (*Dasineura rubiformis*) prevents seed formation by inducing galls on *A. mearnsii* flowers, significantly reducing seed production (Impson et al., 2021). *Bacillus subtilis* was tested against *Ceratocystis fimbriata*, a fungus affecting *A. mearnsii* seedlings, and proved effective in *vitro* but ineffective in *vivo* (Mezzomo et al., 2019). To counteract *A. mearnsii'*s high seed production, seed-feeding *Melanterius* weevils have been introduced as biocontrol agents (Impson, 2005; Rojas-Sandoval and Pasiecznik, 2022). Studies indicate these weevils significantly reduce seed production but are more effective as a supplementary rather than a standalone control method (Strydom et al., 2017).

2.3.3.3 Industrial utilization

Repurposing *Acacia mearnsii* for economic use is an effective control strategy. Its products are utilized in textile, animal nutrition, and healthcare industries (Chan et al., 2015). Tannin extract from *A. mearnsii* bark is preferred in leather production because it is highly soluble, light coloured, and has low viscosity properties (Ogawa and Yazaki, 2018). It also enhances porosity and air permeability, improving breathability in leather products (Kuria, 2015). In animal nutrition, tannin extract has been shown to enhance growth and feed efficiency in goats and lambs (Pimentel et al., 2021; Costa et al., 2021). It also possesses anti-parasitic properties, significantly reducing gastrointestinal helminths in sheep (Cenci et al., 2007). Additionally, tannin extract mitigates methane emissions from cattle and reduces urinary nitrogen losses, benefiting both livestock and the environment (Silva et al., 2024; Pimentel et al., 2021). Its antioxidant and anti-inflammatory properties contribute to animal health, and its use in human healthcare has been explored in Japan since the late 2000s (Venter et al., 2024; Ogawa and Yazaki, 2018). Beyond tannin extraction, *A. mearnsii* wood is commonly used for charcoal and firewood (Chan et al., 2015). Recent studies highlight its potential in pulp and paper production, where it meets essential fibre quality standards (Coldebella et al., 2023; Neiva et al., 2024). *A. mearnsii* outperforms Eucalyptus grandis in pulp yields, increasing its industrial viability (Giesbrecht et al., 2022). Industrial use of *A. mearnsii* presents a dual advantage—economic gain while controlling its spread.

2.3.4 Wood-based biochar and its agricultural benefits

Biochar is a byproduct of thermochemical conversion of feedstock through pyrolysis, producing biofuel (Sadasivam and Reddy, 2015). The wide-ranging adoption of biochar in agricultural systems stems from its proven efficacy of enhancing soil quality and promoting crop growth (Shang, 2019). Deriving biochar from wood has become increasingly prevalent in recent times. Cho et al. (2024) postulated that applying wood-based biochar in lettuce cultivation improved organic matter by 29%, available P by 32% and pH slightly by 4.2% compared to the control. Furthermore, nutrient uptake increased following biochar application, indicating betterment in nutrient retention and availability. Burgeon et al. (2022) assessed the efficacy of different modalities (fresh and century-old) of wood-based biochar on biogeochemical cycling. The findings revealed that fresh biochar restricted nitrate and potassium leaching while increasing phosphate availability. A century-old biochar increased total N, available K and Ca in soil, with a greater impact on Mg cycling. Thus, both biochar modalities contributed significantly to soil nutrient cycling.

In the organic agricultural soils of the US, wood-derived biochar increased the retention of soil readily available N and P by 33% and 39%, respectively. It further significantly enhanced the availability of ammonium and mineralizable nitrogen (Figure 2.11) (Gao et al., 2016).

In addition to nutrient cycling and retention, biochar has been adopted for contributions in carbon (C) sequestration owing to its stability in soil (Wang et al., 2016). A study that aimed to evaluate the influence of biochar on the structural changes of soil organic carbon (SOC) (Han et al., 2024) revealed that biochar induced an inhibitory effect on SOC mineralization. This was observed through CO_2 retention in humic-acid like (HAL) and fulvic-acid like (FAL) components, suggesting storage of C within the biochar-treated soil. Furthermore, in a modelling study (Wang et al., 2016), biochar was projected to reduce about 1.8 Pg CO_2-C of net greenhouse gas (GHG) emission, demonstrating a significant C storage potential. Similarly, biochar from wood, which was investigated for its potential to capture atmospheric CO_2, effectively absorbed CO_2 in humid conditions, further underscoring the role of wood-derived biochar in carbon capture and sequestration (Mamaghani et al., 2024).

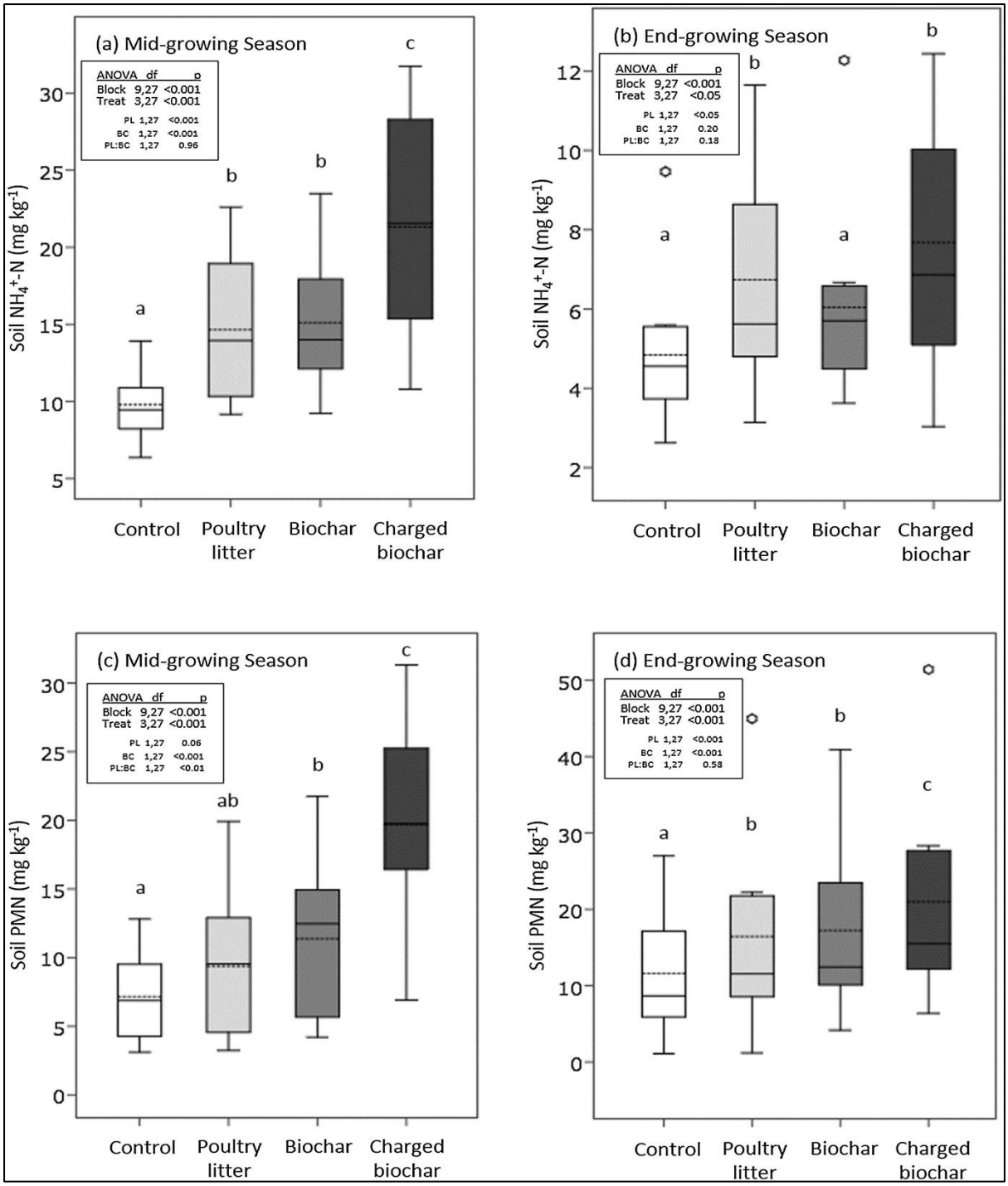


Figure 2.11: Soil extractable NH_4^+ at (a) mid-growing and (b) end-growing seasons; and soil potentially mineralizable nitrogen (PMN) at (c) mid-growing and (d) end-growing seasons in response to poultry litter, biochar and co-application (Gao et al., 2016).

Soil moisture dynamics are also influenced by wood-based biochar. The observations on silica-based sandy soils indicated improvement in soil moisture retention, plant available water, moisture at field capacity and wilting following amendment by maritime pine biochar (Santos

et al., 2022). Correspondingly, Kameyama et al. (2019) revealed that biochar produced from wood chips exhibited greater water-retention capabilities compared to other biochar modalities when pyrolyzed at higher temperatures (600ºC – 800ºC). The observed enhancement in moisture holding capacity can be attributed to the decreased hydrophobicity index of wood biochar at elevated pyrolysis temperatures, which facilitates increased water retention (Kameyama et al., 2019). Amendment of degraded soils by incorporated SDN and *A. mearnsii* biochar presents an opportunity to reverse soil degradation due to moisture and nutrient capacity contained in these items.

South Africa is among the most heavily invaded countries by *Acacia mearnsii*. Its adaptability to diverse environmental conditions complicates control efforts. Mechanical removal is effective but impractical for large-scale management due to labour and time constraints. Biological control methods have reduced seed production but remain insufficient in depleting dense seedbanks. Industrial utilization of *A. mearnsii* offers a sustainable approach that benefits both the economy and the environment. However, control efforts are often limited to targeted areas, leaving rural regions—where *A. mearnsii* reduces already scarce arable land—struggling with its encroachment. This invasion negatively impacts agriculture, the environment, and livelihoods. The potential of *A. mearnsii* wood for biochar production remains underexplored.

2.4 Napier Grass Production: An Alternative Approach

Napier grass (*Pennisetum purpureum*), commonly referred to as elephant grass, is a hardy, deep-rooted, and perennial C4 forage crop adapted to tropical environments (Islam et al., 2023; Nyambati et al., 2010; Waramit & Chaugool, 2014). While native to Sub-Saharan Africa, it has successfully established in various tropical and subtropical regions (Negawo et al., 2017, Nyambati et al., 2010). Napier grass thrives on a variety of growth conditions but requires warm temperatures and adequate moisture supply as cold and drought limit its optimum production (Turano et al., 2016). Napier grass (*Pennisetum purpureum*) exhibits optimal growth on well-drained soils with adequate nutrient levels (Ishii et al., 2013). However, studies have reported an outstanding resilience and adaptation to soils contaminated with sodium (Na) and cadmium (Cd), which demonstrate a phytoremediation potential of the grass (Ishii et al., 2013, Rahman et al., 2022). The paucity of pests and diseases that attack Napier grass permits continuous and sustainable production (Ishii et al., 2013).

The high-yielding, fast-growing capacity and nutritional value of *P. purperium* enables a valuable feed source, producing high digestibility biomass which benefits livestock (Taherabadi and Kafilzadeh, 2023). The findings in **Table 2.3** highlight the nutritional quality of selected Napier grass varieties, demonstrating its viability as a feed crop. Cattle supplied with Napier grass significantly improved milk production, averaging 11kg/day and gained live-weight (Islam et al., 2024). In goats, the Napier fodder diet was found to achieve optimum growth but with a lower feed conversion ratio (FCR). This parameter signifies efficient production, where less feed attains optimal results (Aswanimiyuni et al., 2018). *Pennisetum purpureum* (Napier grass) exhibits versatile forage potential, extending beyond terrestrial livestock to aquatic species. A recent study by (Klahan et al., 2024) demonstrated the prospective use of Napier grass as a feed supplement for Nile tilapia (*Oreochromis niloticus*), highlighting its potential to obtain optimal fish growth performance while reducing feed input costs.

Table 2.3: Nutrient composition of selected Napier grass cultivars (Turano et al., 2016).

Parameter	Variety			
	Bana	**Mott**	**MB4**	**N51**
Dry matter (%)	18.0	20.6	20.4	17.9
Ash (%)	14.1	12.7	13.2	11.3
Crude protein (%)	8.3	6.5	7.4	7.5
Digestibility of protein (%)	57.0	56.7	62.5	55.7
NDICP (%)	2.8	2.2	2.8	2.9
Starch (%)	1.7	1.3	1.8	1.2
NFC (%)	10.9ab	9.6ab	8.8b	9.6ab
Soluble carbohydrate (%)	5.8	3.0	3.6	4.6
ADF (%)	47.8	52.9	51.6	49.7
NDF (%)	68.4	72.2	72.2	73.0
Lignin (%)	5.5	6.2	6.3	6.6
TDN (%)	50.3	44.7	49.2	51.2
ME (Mcal/kg)	1.7	1.7	1.6	1.7
NEL (Mcal/kg	0.86	0.70	0.78	0.80
NEM (Mcal/kg)	0.83	0.66	0.8	0.86
NEG (Mcal/kg)	0.33	0.10	0.25	0.31

All data, except dry matter, are reported on a dry matter basis. The following abbreviations are used throughout: Acid Detergent Fiber (ADF), Metabolizable Energy (ME), Net Energy for Growth (NEG), Net Energy for Lactation (NEL), Net Energy for Metabolism (NEM), Neutral Detergent Fiber (NDF), Neutral Detergent Insoluble Crude Protein (NDICP), Non-Fiber Carbohydrate (NFC), and Total Digestible Nutrients (TDN)

2.5 Integration and Interactions

SDN waste, *A. mearnsii* invasion, soil degradation and livestock shortages remain the multifaceted concerns that are unfortunately highly prevalent in low-income areas. Soiled nappies contain nutrients from urine and faeces, and superabsorbent polymers that retain substantial volumes of moisture (Xu et al., 2024). Biochar has been widely applied in agriculture and demonstrates a positive efficacy (Manirakiza et al., 2024).

The potential of utilizing SDN and biochar from black wattle as soil amendments, on a degraded land not only addresses pollution and encroachment, but also an opportunity to enhance Napier grass growth. The successful production of the elephant grass signifies prospective alleviation of livestock fodder shortages.

Degraded soils in South Africa are often defined by inadequate nutrient levels, poor water-holding capacity, degraded structure, and reduced vegetation cover, with soil erosion being a primary driver of this degradation (Endale et al., 2023, Zia-ur-Rehman et al., 2016). While amending the soil with SDN and biochar can influence moisture and nutrient dynamics, the robust Napier grass can prevent soil erosion and improve soil structure. The synergistic interactions between SDN, *Acacia mearnsii* biochar, and Napier fodder growth on a degraded land can mitigate soil degradation through enhanced remediation.

2.6 Conclusions and Future Directions

This comprehensive review highlighted the critical global environmental issues of SDN waste, soil degradation and the proliferation of the invasive black wattle. It is apparent that managing SDN waste is a global challenge, but it extensively manifests in low-income areas, including South Africa. SAP used in nappies revealed contrasting findings on the efficacy of its agricultural application with some benefits reported to be due to improvement of soil moisture holding and providing nutrients. The mechanical, biological and industrial strategies of controlling *Acacia mearnsii* could be inferior to biochar production which has been reported to improve soil nutrient cycling, microbial community and overall soil quality. These benefits, of improved productivity, due to application of SDN and biochar from *A. mearnsii*, have not been reported for soils in communal lands of South Africa, which are highly degraded. The co-application of SDN and black wattle biochar as soil amendments to produce Napier grass could provide a promising opportunity to reverse soil degradation, while addressing SDN pollution and black wattle invasiveness.

CHAPTER 3

Napier (*Pennisetum purpureum*) Dry Matter Yield and Nutrient Dynamics: Unravelling the Impacts of Entrenched Nappies and *Acacia mearnsii* Biochar on Degraded Soils

3.1 Introduction

Modern-day disposable nappies provide hygiene and convenience, improving parenting for mothers (Khoo et al., 2019). The affordability of these items eases feasibility for global utilization. Kakonke et al. (2019) reported that disposable nappies were utilized by 80% of households in South Africa despite the country being dominated by low to middle-income households. However, the scaled usage of these items aligns with waste quantities generated. The European Union generates approximately 40 000 units of Diaper waste every minute (Mendoza et al., 2019b) contributing to over 500 000 tons annual waste. South Africa alone produces over one million tons of SDN annually (Khanyile et al., 2020). Despite being mandated to provide solid waste management (SWM) services, South African municipalities often struggle to deliver adequate waste collection and disposal services to rural communities (Kalina et al., 2003).

Residents of communal lands in the upper uMkhomazi River Catchment, KwaZulu-Natal Province, South Africa, are among the communities severely impacted by inefficient waste management services. This often results in indiscriminate disposal of waste. Of particular concern is the rise in indiscriminate disposal of SDN which have become affordable globally in the past decade (Aishwariya and Priyanka, 2020). SDN often accumulate in illegal dumpsites, along roadsides, or infiltrate water bodies, contributing to varying degrees of soil, water, and air pollution (Godfrey and Oelofse, 2017, Remigios, 2014). The absence of waste collection infrastructure and services in some of these areas justifies the need to identify approaches aimed at repurposing SDN to support the reduction of their uncontrolled disposal. The need for to reduce uncontrollable disposal is particularly important in areas with degraded land where productive soils are at a prime.

In addition, land degradation is both an environmental and a socio-economic concern in today's world with a rapidly growing population and demand for food and space. Several factors including population growth, soil properties, slope, climate, vegetation and unsustainable land use contribute to degradation (Bunning et al., 2016). At a global level, degradation engulfs over 20% of total land and exacerbates at a rate of approximately 10 billion hectares per annum (Bateman and Muñoz-Rojas, 2019). Sub-Saharan Africa (SSA) houses more than one billion people who depend on subsistence farming (Nkonya et al., 2008) and about 30% inhabit degraded, unproductive soils (Nkonya et al., 2016). In South Africa, more than 60% of the total land endures degradation (Mani et al., 2021). The upper uMkhomazi catchment, over 7500ha of communal lands endure land degradation (Affairs, 2018). The loss of productive soil surface due to land degradation is typified by low crop and grass productivity thus contributing to food insecurity (Utuk and Daniel, 2015).

The quantity and quality of livestock fodder availability are critical in smallholder farming systems. However, its scarcity still remains a constraint for resource-limited farmers, especially in winter (Mthembu et al., 2017). Various factors lie behind grass shortages. Sprynchuk et al. (2023) highlight the impact of erratic climate including recurring droughts and flooding. In addition, scarcities may arise from poor management techniques that often permit overgrazing and subsequent land degradation (Abdelsalam, 2021). Moreover, bush encroachment by invasive woody and thorny trees can deplete native grasses, resulting in lack of feed availability (Ayalew and Mulualem, 2018). Lastly, limited land may deprive farmers from producing and managing feed resources, leading to shortages (Kamanzi, 2012). Access to quality forages could reduce the famer's input costs by more than 30% (Zailan et al., 2018). Napier grass (*Pennisetum purpureum*) is one of the main crops that smallholder farmers often rely on. It is perennial, vigorous and high yielding grass, which is resistant to unfavorable weather conditions (Nyambati et al., 2010).

There is a growing research interest in exploring the potential benefits of recycling nappies for agricultural applications (Al-Jabari et al., 2019, Espinosa-Valdemar et al., 2014, Ferronato et al., 2020, Keshavarz and Farahbakhsh, 2012, Moslemi et al., 2011). For instance, in assessing the application of superabsorbent polymer recovered from SDN for enhancing soil irrigation management, Al-Jabari et al. (2019) postulated that incorporating recycled superabsorbent polymer into soil significantly reduces water loss through percolation, leading to enhanced

irrigation efficiency and improved plant growth. Other studies have demonstrated that edible mushrooms can be cultivated on a substrate composed of SDN and gardening waste, providing a viable and innovative treatment alternative for urban organic waste (Espinakosa-Valdemar et al., 2014). Additionally, agricultural application of superabsorbent polymers derived from nappies was observed to improve crop water-use efficiency (Keshavarz and Farahbakhsh, 2012). Furthermore, incorporating superabsorbent polymer in soil reduced water evaporation rates and significantly improved yields (Moslemi et al., 2011). The ability to hold water and supply nutrients means that disposable nappies could be valuable in terms of rehabilitating degraded agricultural lands to improve plant productivity.

The primary objective of this chapter was to evaluate the impact of incorporating SDN and black wattle biochar on the yield and nutritional quality of Napier grass in degraded agricultural landscapes. It was hypothesized that:

(i) Incorporating SDN into the soil would enhance the aboveground dry matter (DM) yield and nutritional quality of Napier grass, as compared to the control treatment, and

(ii) SDN would be more effective in improving DM yield and nutritional quality of Napier grass when applied in combination with fertiliser and biochar as compared to the control.

3.2 Methods and materials

3.2.1 Site description

A field experiment was initialized in December 2022 and ran until February 2024. The trial site was situated in the upper uMkhomazi catchment, specifically in eMangwaneni village (29°42'25.38"S; 29°48'5.85"E), approximately 10 km northeast of Bulwer, within the Dr. Nkosazana Dlamini-Zuma Local Municipality, southern KwaZulu-Natal Province, South Africa (Figure 3.1).

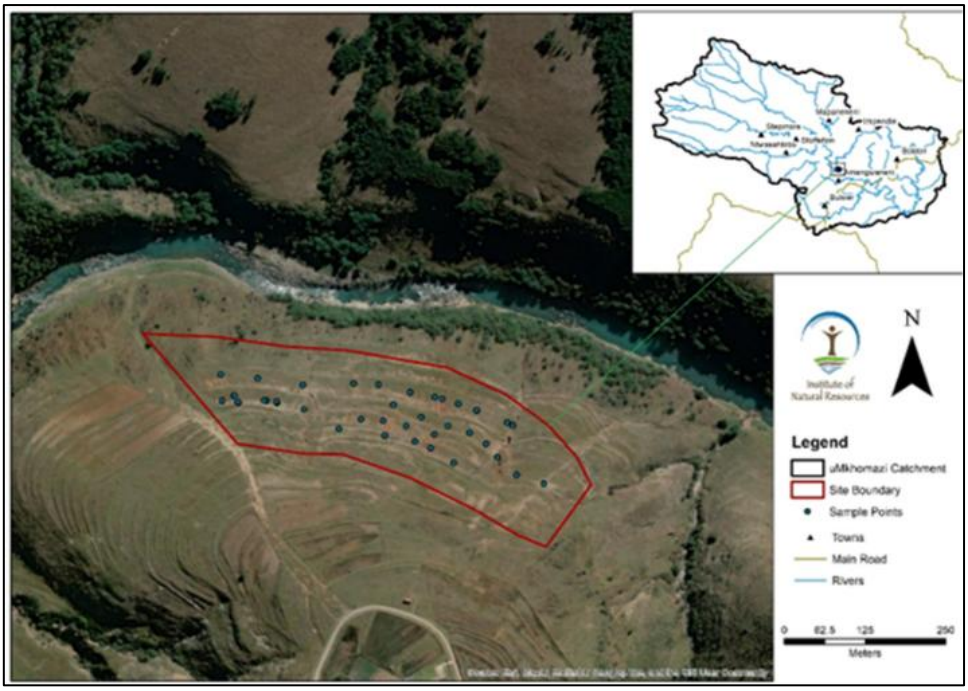


Figure 3.1: Study site locality map.

The upper uMkhomazi region receives an average rainfall of 948 mm annually, primarily intense between October and April, and is underlined by Shale and mudstones (COGTA, 2020, Madibe, 2021). The area experiences a temperate climate, with temperatures fluctuating between below 0°C during winter and up to 30°C during summer. The trial site contains grass patches of perennial Ngongoni grass (*Aristida junciformis*), which is an indicator of degraded grassland. The topography comprises rolling hills to mountainous areas and is primarily suited for livestock production. Alien invasive black wattle (*Acacia mearnsii*) prevails in most valleys in the area and along the uMkhomazi River. The experimental site was selected because it is an abandoned agricultural land, has signs of degradation, and the soils have sufficient depth for plant establishment.

3.2.2 Soil sampling

Soil samples were collected from the experimental site in December 2022, prior to planting. Ten soil samples were collected from a 200m long contour, at intervals of 20 m, using a bucket auger. Due to the shallow nature of degraded soils within the experimental site, soils were only sampled from 30 cm depth. Collected samples were put into labelled bags and air-dried to constant weight. The collected soil samples were stored in soil sample boxes and submitted to

the KwaZulu-Natal Department of Agriculture's Fertiliser Advisory Service at Cedara College of Agriculture for analysis. The initial soil chemical and physical properties were assessed, including total nitrogen (N), soil organic carbon (SOC), pH, phosphorus (P), potassium (K), manganese (Mn), zinc (Zn), calcium (Ca), magnesium (Mg), copper (Cu), and clay content. These parameters were analysed using standard techniques (Manson and Roberts, 2000), and the results are presented in**Table 3.1**.

Table 3.1: Topsoil (0-30cm) fertility status of the experimental site prior to planting.

Soil property	Unit	Contours		
		Lower	Middle	Upper
Clay	%	43.5	42.5	43.5
pH	KCl	4.24	4.28	4.09
Organic carbon	%	1.35	1.70	1.20
N	%	0.12	0.14	0.08
P	mg g^{-1}	≤0.05	≤0.05	≤0.05
K	mg g^{-1}	0.17	0.17	0.15
Ca	mg g^{-1}	0.80	0.83	0.73
Mg	mg g^{-1}	0.41	0.47	0.36
Total cations	cmol/L	8.22	8.75	7.555
Acidity	cmol/L	0.39	0.33	0.59
Zn	mg/L	0.80	0.85	0.60
Mn	mg/L	10.0	12.0	10.0
Cu	mg/L	2.60	2.90	2.95

N= total nitrogen; P= available phosphorus…….

3.2.3 Land preparation and source of planting material

The experiment was established along a degraded contour on middle-slope. After soil sampling, a 200 m long trench was opened along the contour using a tractor drawn mould board plough. The trench was then refined manually using spades, picks, and hoes to achieve a width and depth of 0.60 m and 0.30 m, respectively.

Plant propagation was conducted using wild populations of Napier grass (*Pennisetum purpureum*) harvested in Camperdown, KwaZulu-Natal, South Africa. Napier grass slips used for plant establishment were obtained by cutting the parent plant into short stems or cuttings. Each stem or cutting had a minimum of three healthy nodes.

3.2.4 Experimental design, soil amendments and plant propagation

The experiment adopted a randomized complete block design (RCBD) with three replications per treatment. A total of 21 field plots, arranged along a contour, were prepared, each measuring 9m in length, 1.2m in width, and covering an area of 10.8m². The experiment consisted of seven treatments which included: a control (CON), nappies only (NO), biochar only (BO), nappies plus biochar (NB), nappies plus fertilizer (NF), fertilizer plus biochar (FB); and nappies plus fertilizer plus biochar (NFB).

3.2.4.1 Application of soil amendments

Soil amendments were only applied at planting and not during the regrowth period. For treatments with nappies (i.e. NO, NB, NF and NFB), an extra 10cm deep and 20cm wide small trench was dug at the base of original trench. SDN obtained from households, preparatory schools, and illegal dumpsites were laid next to each other at batches of 3 abreast along the plots. Approximately 90 batches of nappies were fitted in each plot which amounted to approximately 270 nappies per plot. Soil was used to cover the nappies, and to ensure that the trench surface of plots with nappies was at the same level as the other treatment plots without nappies. Biochar was produced from an invasive black wattle (*Acacia mearnsii*) using a 210-litre hand-fed pyrolysis kiln (Jansmior Engineering, Hartebeespoort, South Africa). It was crushed and sieved through a 10 mm mesh before application to the respective treatment plot (i.e. BO, NB, FB and NFB) at 10 000kg ha^{-1} application rate as applied by Ndor et al. (2015). For treatments with fertilizers (i.e. NF, FB and NFB), a combination of synthetic nitrogen (N) and phosphorous (P) were applied at rates of 150 kg ha^{-1} of nitrogen and 20 kg ha^{-1} of phosphorus respectively. The application of fertilizers was based on the recommendations from the KwaZulu-Natal Department of Agriculture's Fertilizer Advisory Services at Cedara College of Agriculture, Pietermaritzburg, South Africa. The nitrogen and phosphorus were sourced from limestone ammonium nitrate (LAN 28%) and single super phosphate (SSP 10.5%), respectively.

3.2.4.2 Plant propagation

The experiment was established on the 22nd of December 2022. Napier cuttings were planted 15 – 20 cm deep at an angle of 30° – 45° in the ground. To allow for rapid establishment of the Napier hedgerow, a staggered double row with inter-row spacing of 30 cm and intra-row spacing of 60 cm was used. There were 30 Napier plants per treatment, which equated to a population density of 55 000 plants per hectare.

3.2.5 Monitoring and data collection

In this study, morphological (tiller height and count), physiological (SPAD-based chlorophyll content), agronomic (leaf, stem and total dry matter yield, and leaf-stem ratio) and feed quality data were collected.

3.2.5.1 Tiller number counts and heights

Plant growth assessment for each treatment involved measuring Napier grass stem height (cm) from the root collar to the terminal bud using a tape measure, while tiller count was determined through simple arithmetic counting. Measurements were taken weekly, starting nine weeks after planting, from the same five randomly selected plants per treatment. To maintain consistency, these plants were marked with danger tape to ensure repeated measurements were conducted on the same individuals.

3.2.5.2 SPAD-based leaf chlorophyll content

In both growth cycles, leaf chlorophyll content was estimated using a SPAD meter (SPAD-502, Minolta Co., Japan), which provides dimensionless Soil Plant Analysis Development (SPAD) values. The SPAD-502 is a widely used hand-held device known for its rapid, accurate, and non-destructive measurement of leaf chlorophyll concentrations. Measurements were taken at a central point on the leaflet, positioned between the midrib and the leaf margin. A single SPAD reading was recorded from the uppermost fully expanded leaf displaying the top visible dewlap (TVD) or a distinct collar.

3.2.5.3 Harvesting, DM Yield and feed analysis

In the first growth cycle, Napier grass (*Pennisetum purpureum*) was harvested 20 weeks after planting. In the second growth cycle, plants were harvested 24 weeks after regrowth. In both growth cycles, Napier grass biomass in each plot was harvested from three 1 m long transects within each treatment. This was achieved by placing a 9 m measuring tape in each plot and all plants that were within 2 – 3 m, 4 – 5 m and 6 – 7 m from the edge of the transects were cut at 30 cm height using secateurs. To minimize external influence ("edge effect"), plants that were within 0 – 2 m and 7 – 9 m transects (i.e., on the ends of the transects) were not considered for biomass sampling. Harvested biomass, separated as stem and leaf, from each plot was placed in labelled brown bags for processing in the laboratory. The stem and leaf fractions were separately oven-dried at 65 °C for 72 hours until a constant weight was achieved (Dokbua et al., 2021) and then weighed to determine their dry mass.

Each growth cycle, the oven-dried leaf and stem biomass fractions were combined and finely ground for feed quality assessment. The comprehensive feed analysis encompassed nutritive parameters, including crude protein (CP), neutral detergent fibre (NDF), acid detergent fibre (ADF), ash content, and macro- and micronutrient concentrations. The CP was determined by Kjeldahl technique (A.O.A.C, 1990) and nitrogen (N) calculated by CP/6.25. Other feed quality nutritive indices, NDF and ADF, for Napier grass were measured as indicated by (Van Soest et al., 1991). The concentrations of macronutrients (P, K, Ca, Mg, and Na) and micronutrients (Fe, Mn, Zn, and Cu) in plant tissue were determined using Inductively Coupled Plasma - Optical Emission Spectrometry (ICP-OES) (SOP, 2005).

Nutrient uptake was determined as a product of mineral nutrient concentration and dry matter yield (Buchi et al., 2015):

$$\text{Nutrient uptake} = \frac{\text{nutrient concentration (\%)}}{100} \text{ x DM yield}$$

3.2.6 Statistical analysis

All collected data were assessed for normality using the Shapiro-Wilk test before analysis. Statistical analyses for tiller height, tiller number, SPAD-based chlorophyll content, dry matter yields, and nutritional composition were conducted using STATISTICA 10.0 software. A 2 ×

7 factorial analysis of variance (ANOVA) was performed to evaluate the effects and interactions between two growth cycles and seven used disposable nappy treatments. Treatment means were compared using the Duncan Multiple Range Post Hoc Test (DMRT) at $p \leq 0.05$, with significance levels denoted as $*p<0.05$, $**p<0.01$, and $***p<0.001$, while NS indicated non-significance. Pearson's simple correlation analysis was conducted to examine the relationships between dry matter yield and tiller height and number.

3.3 Results

3.3.1 Dry matter (DM) yield

A two-way ANOVA revealed significant interaction between growth cycle and treatment in terms of leaf, stem and total dry matter of Napier grass (Table 3.2)

Table 3.2: A two-way ANOVA of leaf, stem and total dry matter (DM) yield of Napier grass following ap-plication of seven treatments and two growth cycles.

Factor	Leaf DM	Stem DM	Total DM
		ton ha^{-1}	
Growth cycles			
GC1	1.67±0.13	1.12±0.12	2.79±0.25
GC2	1.54±0.11	1.42±0.13	2.96±0.23
Treatment			
NFB	3.02±0.15	2.74±0.17	5.75±0.28
NO	1.31±0.08	0.87±0.11	2.18±0.18
CON	0.80±0.09	0.51±0.12	1.31±0.13
NB	1.45±0.16	1.05±0.17	2.49±0.32
FB	1.59±0.11	1.25±0.12	2.84±0.19
NF	2.43±0.18	2.07±0.20	4.50±0.36
BO	0.64±0.07	0.40±0.09	1.04±0.15
F-statistics			
Growth cycle	2.34ns	8.33*	0.92ns
Treatment	56.61***	39.29***	55.82***
Growth cycle×treatment	5.80***	2.26*	4.27***

Variable means within the same column sharing the same letter are not significantly different (P>0.05) based on the Duncan Multiple Range Test (DMRT); ns = not significant.

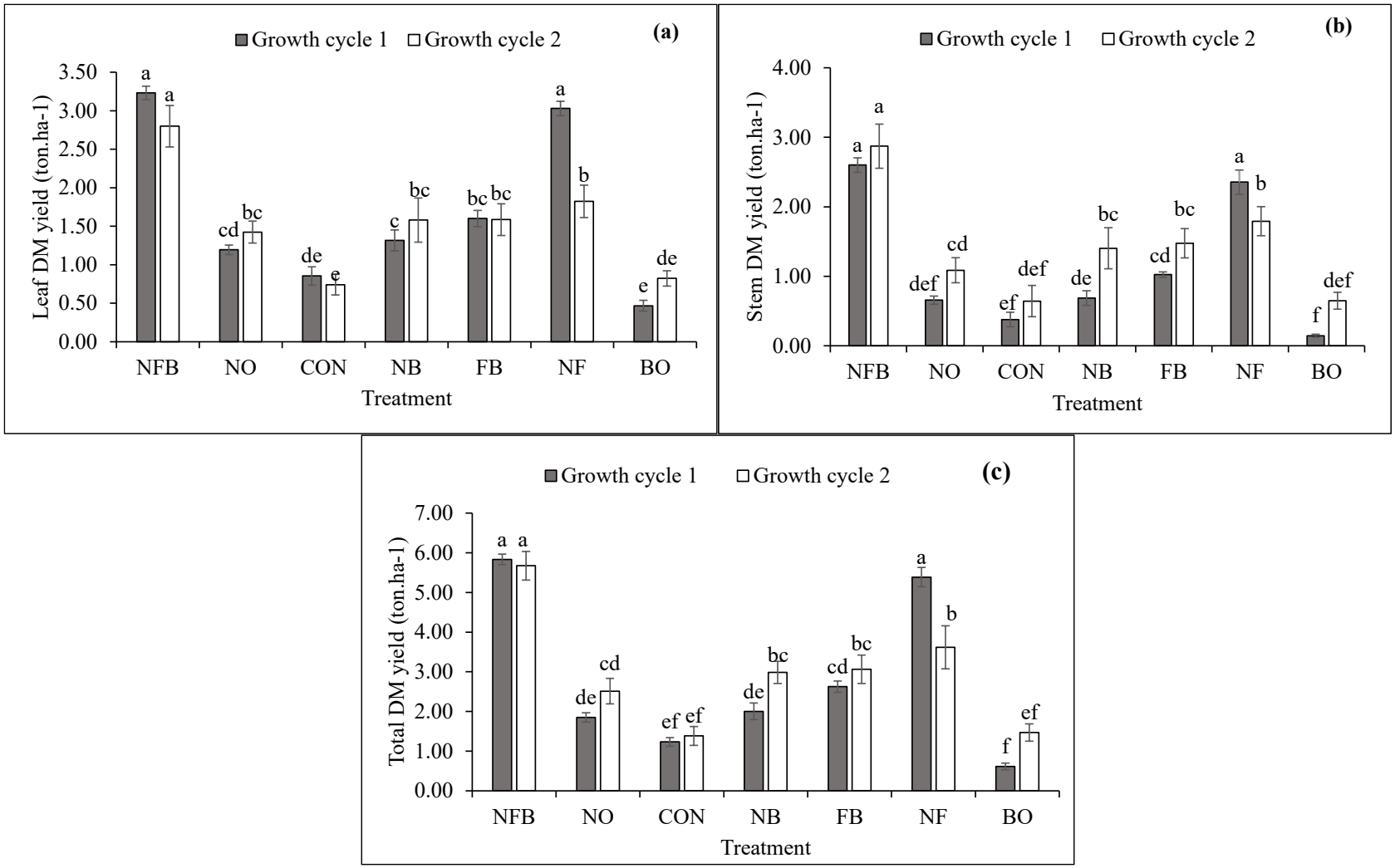


Figure 3.2: Interactive effect of growth cycle x treatment on a) leaf, b) stem and c) total DM yield as influenced by seven treatments.

Figure 3.2a presents data on aboveground dry matter (DM) yields of Napier grass, including stem and leaf DM yield (ton ha^{-1}) as well as total DM yield (ton ha^{-1}). A Student's t-test comparing the two growth cycles indicated that leaf DM yield for NFB and NF was significantly higher in the first growth cycle than in the second (Figure 1a). However, no significant differences were observed in leaf DM yields for CON, NB, and FB between the two cycles. In contrast, BO and NO exhibited significantly higher leaf DM yields in the second growth cycle. On average, across both cycles, NFB and NF produced the highest leaf DM yield, whereas BO and CON recorded the lowest.

The Student's t-test results comparing the first and second growth cycles showed that stem DM yield for NO, NB, FB, and BO was significantly higher in the first growth cycle than in the second (Figure 1b). Similarly, NF exhibited a significantly greater stem DM yield in the first cycle compared to the second. However, stem DM yields for CON and NFB remained statistically similar between the two cycles. When averaged across both cycles, NFB, followed by NF, achieved the highest stem DM yield, while BO and CON recorded the lowest (**Figure 3.2b**).

In the initial growth cycle, the highest (5.83 ton ha^{-1}) and lowest (0.47 ton ha^{-1}) mean aboveground total dry matter (DM) yields were recorded in the NFB and BO treatments, respectively (**Figure 3.2c**). In the subsequent growth cycle, the highest (5.67 ton ha-1) and lowest (1.38 ton ha-1) mean aboveground DM yields were found in the NFB and CON treatments, respectively. The results of the Student's t-test indicated that the total DM yield of the NF treatment was significantly higher in the first growth cycle compared to the second. In contrast, NO, NB, and BO showed a notable increase in total DM yield in the second growth cycle compared to the first. There was no significant difference in total DM yield between the first and second growth cycles for Napier grass amended with NFB and CON. When averaging across both cycles, NFB and NF treatments achieved the highest total DM yields, while BO and CON had the lowest yields (**Figure 3.2c**).

3.3.2 Napier grass tiller number, heights and SPAD-based chlorophyll content

A two-way ANOVA showed no significant interaction between growth cycle and treatment for the tiller height and tiller number of Napier grass. However, the main effects of growth cycle and treatment were found to be highly significant for both tiller height and number. When

averaged across all treatments, tiller heights in the second growth cycle were 2.3 times higher than those in the first growth cycle. Tiller numbers increased by 54% in the second growth cycle compared to the first. On average across both growth cycles, the NFB treatment, followed by NF and FB, produced the highest tiller heights and numbers, while CON and BO had the lowest values at harvest (**Table 3.3**).

Table 3.3: A 2-way ANOVA for tiller height, number and SPAD-based chlorophyll content of Napier grass as affected by seven treatments.

Factor	Tiller height	Tiller number	Chlorophyll
	cm	no plant^{-1}	SPAD units
Growth cycle			
GC1	81±7b	6.8±0.6b	41.3±1.2a
GC2	188±8a	10.5±0.5a	39.3±0.6b
Treatment			
NFB	191±26a	13.4±0.7a	42.3±2.2ab
NO	132±26cd	7.75±1.26cd	38.5±0.9bc
CON	98±23e	6.3±0.9e	37.5±2.2c
NB	121±23d	7.2±0.7de	40.4±0.6abc
FB	139±22c	8.5±0.5c	43.2±1.7a
NF	163±23b	11.0±1.0b	42.4±2.5ab
BO	99±26e	6.5±1.2e	37.8±0.9c
F-statistics			
Growth cycle	661.34***	142.72***	4,42*
Treatment	37.66***	40.95***	3,38**
Growth cycle×treatment	0.75ns	2.15ns	4,98***

Variable means within the same column sharing the same letter are not significantly different (P>0.05) based on the Duncan Multiple Range Test (DMRT); ns = not significant

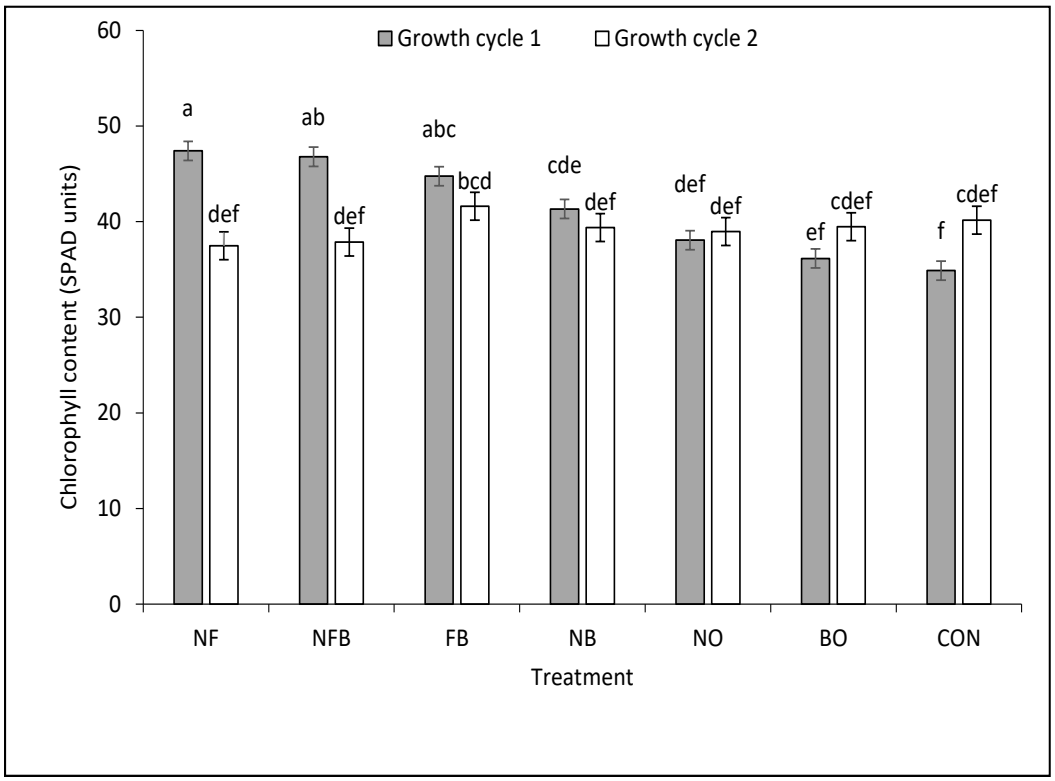


Figure 3.3: SPAD-based chlorophyll content from Napier grass subjected to seven treatments over two growth cycles.

A significant interaction between growth cycle and treatment was observed regarding SPAD-based chlorophyll content. During the first growth cycle, NF and NFB had statistically higher chlorophyll content than BO and CON. The treatment FB was higher than CON in terms of leaf chlorophyll and there was no significant variation between diaper-supplied and no fertilizer treatments (NB and NO) compared to other treatments. During the second growth cycle, only FB was significantly higher than NF in chlorophyll content and no significant variation was observed among other treatments (**Figure 3.3**).

3.3.2.1 Correlations between DM yield and tiller height and number

The correlation analysis examined the relationships between dry matter (DM) yield and key tiller parameters during two growth cycles. In growth cycle one, a positive relationship was observed between DM yield and tiller height (**Figure 3.4a**), indicating that taller tillers contributed to increased biomass production. Similarly, a positive correlation was found

between DM yield and tiller count (**Figure 3.4b**), suggesting that a higher number of tillers resulted in greater yield.

In growth cycle two, the relationship between DM yield and tiller height (**Figure 3.4c**) followed a similar trend as in growth cycle 1, reinforcing the importance of plant stature in biomass accumulation. Additionally, DM yield was positively correlated with tiller number (**Figure 3.4d**), indicating that an increased tiller population remained a key determinant of productivity.

Across both growth cycles, significant differences between treatments were identified at $p \leq 0.05$, as denoted by the lowercase letters in the graphs. These results highlight the consistent influence of tiller height and number on DM yield, emphasizing their role as critical indicators of plant performance under the experimental conditions.

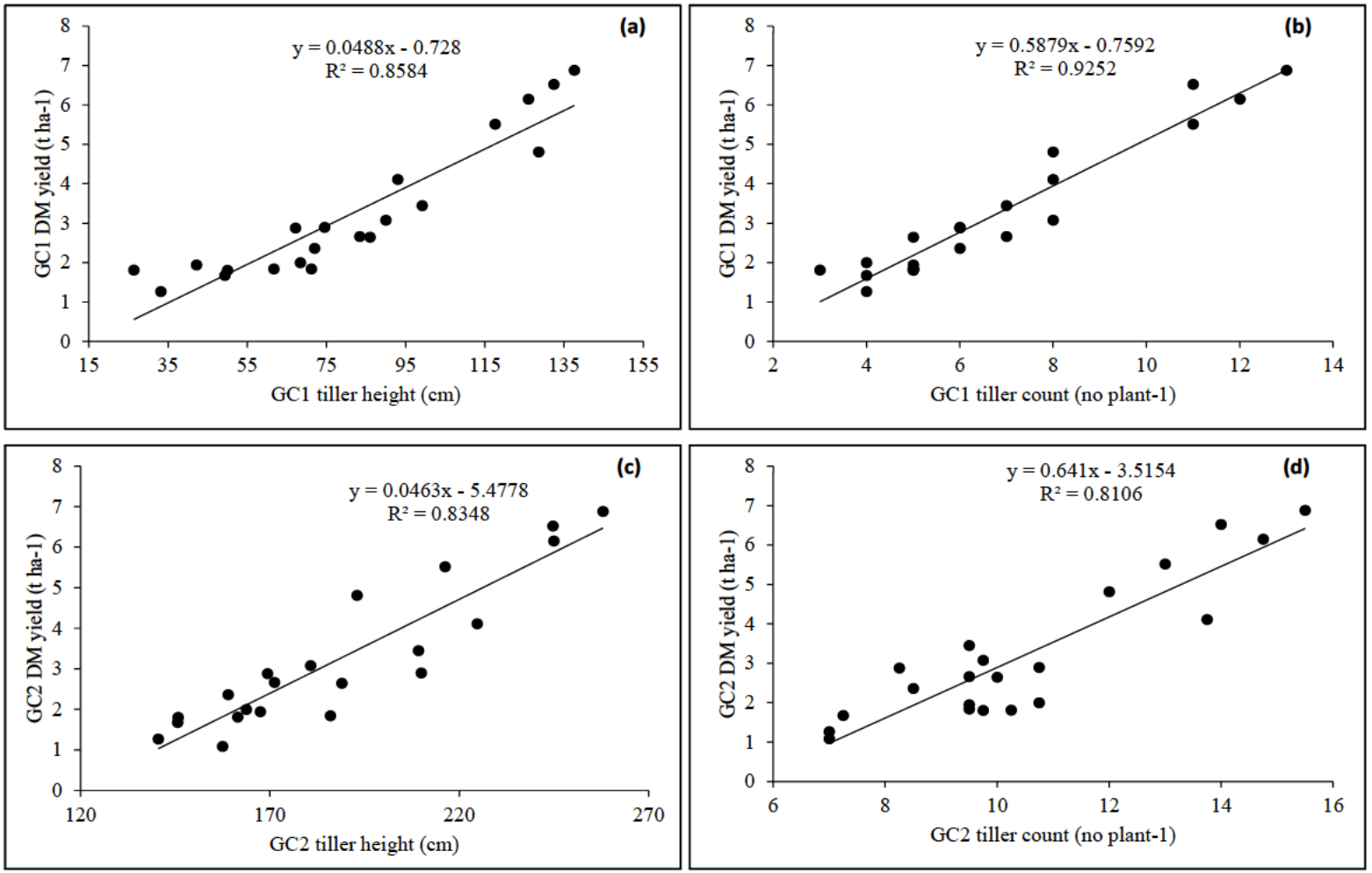


Figure 3.4: Relationship between DM yield and (a) tiller height, and (b) tiller count of growth cycle 1 and (c) tiller height and (d) count of growth cycle 2 at harvesting period.

3.3.3 Chemical composition and mineral concentration of Napier grass

3.3.3.1 Chemical composition of Napier grass

Except for CP, a two-way ANOVA revealed no significant growth cycle × treatment interaction in terms of CP, NDF, ADF, Ash, and Fat. The main effect of growth cycle was highly significant for concentrations of ADF, Ash, and Fat but not for NDF. Except for ADF and Fat, the main effect of treatment was significant for NDF and Ash concentrations (**Table 3.4**).

Table 3.4: A two-way ANOVA for a nutritional value in Napier shoots subjected to seven (7) different treatments.

Factor	CP	NDF	ADF	Ash	Fat
			%		
Growth cycle					
GC1	6.02±0.15a	76.04±0.24a	41.17±0.24a	10.03±0.32b	3.19±0.12a
GC2	4.29±0.08b	75.50±0.25a	40.35±0.24b	12.60±0.20a	1.61±0.03b
Treatment					
NFB	4.84±0.38ab	76.38±0.43ab	41.27±0.32a	10.76±0.77ab	2.40±0.38a
NO	4.88±0.32ab	76.31±0.48ab	41.05±0.56a	11.50±0.56a	2.32±0.31a
CON	5.50±0.59ab	74.81±0.43c	39.81±0.25a	11.44±0.70a	2.35±0.36a
NB	5.25±0.54ab	75.45±0.23bc	41.15±0.57a	12.09±0.65a	2.03±0.27a
FB	5.52±0.52a	75.32±0.51bc	40.44±0.13a	11.94±.0.68a	2.67±0.49a
NF	4.83±0.32b	76.78±0.32a	41.15±0.52a	9.78±0.89b	2.55±0.42a
BO	5.27±0.30ab	75.34±0.39bc	40.48±0.63a	11.68±0.68a	2.49±0.41a
F-statistics					
Growth cycle	162.94***	2.90ns	5.70*	58.85***	215.81***
Treatment	2.83*	2.90*	1.39ns	3.25*	2.08ns
Growth cycle×treatment	2.64*	0.20ns	0.44ns	0.48ns	1.47ns

Variable means within the same column sharing the same letter are not significantly different (P>0.05) based on the Duncan Multiple Range Test (DMRT); ns = not significant.

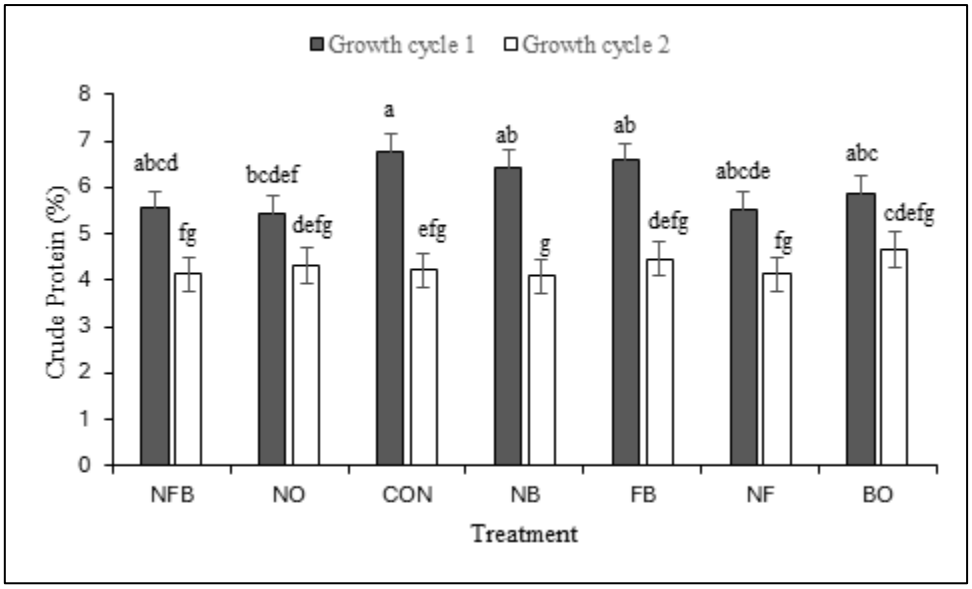


Figure 3.5: Interactive effect of growth cycle x treatment on crude protein of Napier grass. Lowercase letters denote significant differences between treatments at $p \leq 0.05$.

In the first growth cycle, CON followed by FB and NB generally exhibited high CP values as compared to their counterparts. In contrast, the CP values in the second growth cycle were statistically similar across all the treatments. The results of the Student's t-test between the first and second growth cycles showed that CP values for all treatments were significantly greater in the first growth cycle compared to the second (**Figure 3.5**).

3.3.3.2 Macronutrients

A 2-way ANOVA revealed a significant growth cycle × treatment interaction in terms of Napier grass N, Ca and Na uptake but not P, K and Mg. The main effect of growth cycle was, however, highly significant for P, and K, but not for Mg. The main effect of treatment was statistically significant for all measured macronutrients. Uptake of P and K was high in the second growth cycle as compared to the first growth cycle. Considering the treatment effect, NFB followed by NF recorded the highest P, K and Mg uptake as compared with other treatments. CON and BO took up the least amounts of P, K and Mg as compared to their counterparts (**Table 3.5**).

Table 3.5: A two-way ANOVA for macronutrient uptake in Napier grass shoots subjected to seven (7) different treatments.

Factor	P	K	Mg	N	Ca
	kg ha^{-1}				
Growth cycles					
GC1	2.1±0.3 b	44.3±6.5b	7.1±1.0a	26.1±3.7	8.6±1.3
GC2	3.8± 0.4a	73.9±8.1a	6.5± 0.8a	20.1±2.4	4.3±0.6
Treatment					
NFB	5.7±0.7a	114.4±14.7a	13.7±1.2a	44.7±4.8	13.4±2.8
NO	2.6±0.5c	48.5±8.2cd	5.0±0.2cd	16.6±0.6	4.5±0.5
CON	1.3±0.2d	27.7±4.7d	3.3±0.4de	11.3±1.3	3.2±0.6
NB	3.1±0.7bc	59.1±14.4bc	6.0±0.7c	20.3±2.5	5.1±0.7
FB	3.3±0.5bc	61.2±9.2bc	6.7±0.3c	24.9±2.4	6.8±1.1
NF	3.6 ±0.4b	75.4±5.5b	10.5±1.6b	35.7±6.1	10.1±2.3
BO	1.2±0.2d	27.2±9.5d	2.4±0.5e	8.2±1.6	1.9±0.2
F-statistics					
Growth cycle	45.87***	29.13***	0.77ns	10.22*	44.03***
Treatment	20.89***	17.28***	25.80***	27.57***	21.55***
Growth cycle×treatment	1.63ns	1,88ns	2.07ns	3.96*	5.28***

Different lowercase letters denote significant differences between treatments at *P≤ 0.05 **P≤0.01 and ***P≤0.001 for each treatment, ns = not significant.

In both growth cycles, the uptake of N and Ca was generally higher in NFB followed by NF and FB as compared to their counterparts (Fig 5a and b). NB and NO were intermediate in terms of N, Ca and Na uptake during both growth cycles. In contrast, BO and to some extent CON recorded the least amounts of N and Ca in both growth cycles (**Figure 3.6**).

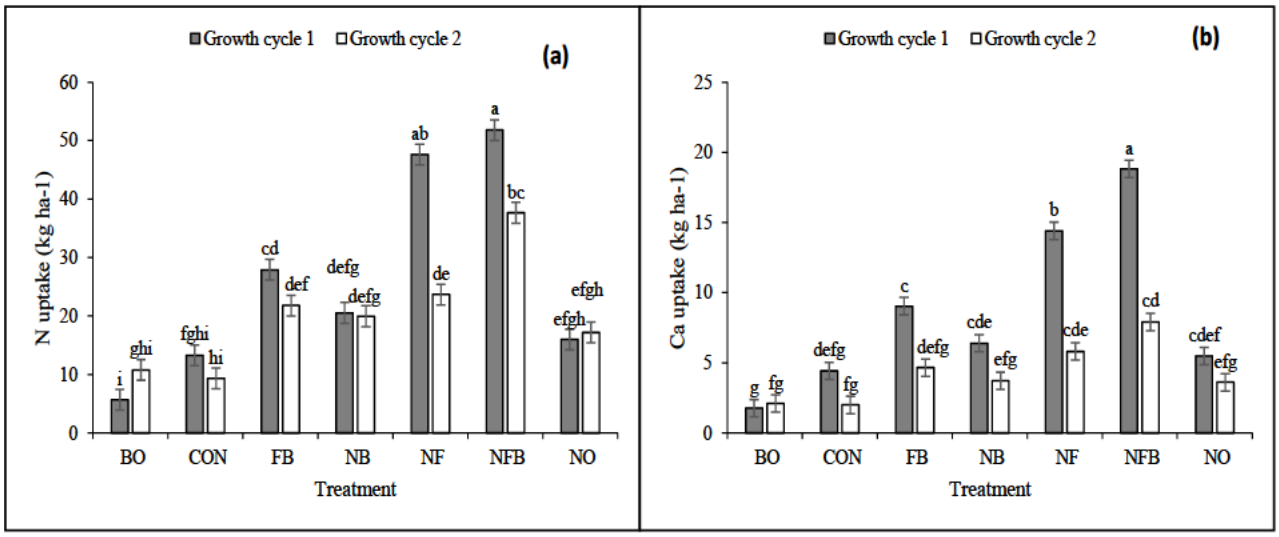


Figure 3.6: Napier grass (a) nitrogen (N) and (b) calcium (Ca) uptake in response to seven treatments and two growth cycles.

3.3.3.3 Micronutrients

A two-way ANOVA highlighted no statistically significant growth cycle × treatment interaction in terms of Fe, Cu, Mn, and Zn concentrations of Napier grass. Except for Mn, the main effect of growth cycle was highly significant for uptake of all measured micronutrients. The main effect of treatment on Fe, Cu, Mn and Zn concentrations was not significant. The concentrations of Fe and Cu were significantly higher in the first growth cycle compared to the second. In contrast, Zn content was significantly greater in the second growth cycle than in the first (**Table 3.6**).

Table 3.6: A 2-Way ANOVA of micronutrient concentrations in Napier grass as influenced by seven treatments.

Factor	Fe	Cu	Mn	Zn
	mg.kg^{-1}			
Growth cycle				
GC1	131±4a	4,6±0.1a	121±6a	4,7±0.4b
GC2	82±4b	3,5±0.3b	117±4a	19,5±0.9a
Treatment				
NFB	98±11a	4,0±0.3a	113±11a	11,3±3.3a
NO	123±12a	4,2±0.5a	116±7a	11,9±3.3a
CON	106±10a	4,3±0.5a	125±9a	14,8±4.1a
NB	111±16a	4,2±0.4a	134±12a	13,5±4.1a
FB	98±11a	4,3±0.3a	111±7a	10,7±2.8a
NF	104±18a	3,8±0.5a	117±10a	10,2±2.9a
BO	104±13a	3,8±0.4a	117±10a	12,2±4.1a
F-statistics				
Growth cycle	65,85***	10,75**	0,41ns	203,54***
Treatment	1,17ns	0,25ns	0,63ns	1,35ns
Growth cycle×treatment	0,41ns	0,38ns	0,69ns	0,74ns

Different lowercase letters denote significant differences between treatments at *P≤ 0.05 **P≤0.01 and ***P≤0.001 for each treatment, ns = not significant

3.4 Discussion

Firstly, it was hypothesised that entrenching SDN would increase the aboveground DM yield of Napier grass as compared to the control (i.e. CON). The findings support this hypothesis in that DM yield of Napier grass amended with nappies only (NO) was increased by 50% and 82% in the first and second growth cycle, respectively, as compared to the CON. SDN contain urine and fecal matter which contain plant essential nutrients such as N, P and K (Yadav et al., 2010). The greater DM accumulation of Napier following entrenching of SDN is most likely due to increased supply of mineral nutrient by nappies in the root zone. As contrasted with the first growth cycle, the effect of increased DM yield of plants amended with nappies as compared with CON was more pronounced in the second growth cycle. This finding could be interpreted to mean that Napier grass exhibited greater root development in the second growth cycle, thus enabling it to explore nutrients inside the nappies to augment nutrient deficits captured from the soil surface. Al-Jabari et al. (2019) reported that recycled superabsorbent polymers from nappies reduce soil water loss through infiltration, enhancing irrigation management and promoting plant growth. Therefore, the role of nappies in terms soil moisture capture and supply, especially during the dry season, cannot be overlooked when assessing the effects of nappies on DM productivity of Napier grass.

Secondly, it was hypothesised that SDN would be more effective in improving DM yield when applied in combination with fertiliser and biochar. The findings support this hypothesis in that DM yield of Napier grass containing NB, FB, NF and NFB was significantly increased by 8, 42, 191 and 215%, respectively, compared to NO during the first growth cycle. In the second growth cycle, the dry matter (DM) yield of Napier grass treated with NB, FB, NF, and NFB increased significantly by 19%, 22%, 44%, and 126%, respectively, compared to the NO treatment. The findings of this study indicate that SDN, when combined with other soil amendments, can enhance grass yields. Across both growth cycles, Napier tiller heights at harvest were positively correlated with aboveground DM yield, and a similar positive correlation was observed between tiller counts and aboveground DM yield. This result suggests that plants supplied with sufficient nitrogen (N) and phosphorus (P) experienced high rates of photosynthesis and consequently vigorous plant growth and development. After moisture, the

metabolic rate in higher plants is considered to be limited by nutrients, especially N and P (Hu et al., 2021). This could in part explain lower DM yield achieved by CON and BO. Additionally, soil physicochemical parameters of topsoil examined before the experiment onset revealed that the site is inherently low in soil fertility, particularly N and P and this could have contributed to observed low DM yields of CON and BO.

Napier grass has been reported to achieve high dry matter (DM) yields of up to 58 tons/ha/year in Thailand (Rengsirikul et al., 2013), 66 tons/ha/year in Malaysia (Halim et al., 2013), and 78 tons/ha/year in Brazil (Oliveira et al., 2014), with an average yield of 28 tons DM tons/ha/year in the literature (Islam et al., 2023). These could be due to environmental factors, treatments and cultivars used in the studies. In contrast, the current study observed much lower DM yields, ranging from 0.61 to 5.83 tons ha^{-1} in the first growth cycle and 1.38 to 5.67 tons ha^{-1} in the second, which are considerably lower than those reported in previous studies (Maleko et al., 2019b; Ntege et al., 2023; Oliveira et al., 2014). The lower DM yields are likely due inherent low soil fertility which consequently reduced tillering. Previous studies have reported Napier grass producing between 49 and 82 tillers per plant, depending on the cultivar (Nyambati et al., 2010). Onjai-Uea et al. (2022) also noted 20 to 36 tillers per plant, influenced by cultivar, plant spacing, and harvest age. The results of this study suggest that the cultivar used, sourced from naturally growing populations, is a low biomass producer, underscoring the need for Napier grass variety improvement programs in South Africa to enhance productivity for agropastoral systems, particularly in communal landscapes.

As with DM yield, leaf chlorophyll content, which in this study was considered as an indicator of leaf photosynthetic capacity, was higher in Napier plants amended with N and P fertilizers (NFB, NF and FB), as compared with their unfertilized counterparts (**Figure 3.3**). The results of this study suggest that nitrogen (N) availability during the early growth stages enhances chlorophyll content in Napier grass. This finding is consistent with the work of Xiong et al. (2015), who showed an increase in SPAD values with higher N supply in seven monocots and dicots. Napier grass, like other C4 species such as maize, sorghum and sugarcane, has high photosynthetic efficiency and highly dependent on inputs of N to achieve optimum production in agricultural landscapes (Ain et al., 2022).

In this study, the nutritional quality of Napier grass was generally not increased by amended SDN. Averaged across the two growth cycles, crude protein (CP) concentration of Napier grass

amended with NO was decreased by 11.3% as compared with the CON (Figure 5). The effectiveness of SDN when applied in combination with other soil amendments (fertilizer and/or biochar) also did not increase CP values of Napier grass as compared with the control. CON plants exhibited, on average, 4.5%, 13.6% and 13.9% higher CP values as compared to that recorded for NFB and NF, respectively. The findings of this study indicate that incorporating SDN into the soil, either alone or in combination with other amendments, does not enhance the crude protein (CP) content of Napier grass in the short term. This outcome aligns with the results of Zewdu et al. (2002), who found that nitrogen (N) fertilization had no significant impact on ash, acid detergent fiber (ADF), neutral detergent fiber (NDF), cellulose, hemicellulose, calcium (Ca), phosphorus (P), in vitro dry matter digestibility (IVDMD), or metabolizable energy (ME) levels. The CP concentrations measured in this study, ranging from 4.8% to 5.5%, fall within the range reported in previous studies on Napier grass in Africa (Gemiyo, 2017; Tavirimirwa et al., 2012). For instance, research by Gemiyo et al. (2017) assessing the nutritional composition of 10 Napier accessions harvested at two-month intervals in Ethiopia found CP values between 4.2% and 6.7%. However, the CP levels recorded in this study are below the recommended minimum of 7% necessary for optimal rumen function in ruminants, as proposed by Nori et al. (2009). Consequently, Napier grass alone may not fully meet the protein requirements of livestock, necessitating supplementation with commercial protein sources or nitrogen-fixing leguminous trees such as *Sesbania* to enhance feed utilization (Manaye et al., 2009; Tessema & Baars, 2004). Additionally, CP content was significantly higher in the initial growth cycle compared to the subsequent one, a trend commonly reported in studies evaluating Napier grass forage quality (Ansah et al., 2010; Rambau et al., 2016).

The fiber fraction concentrations observed in this study are consistent with those reported by Gemiyo et al. (2017), though they generally exceed values documented in previous research on Napier grass (Maleko et al., 2019a; Manaye et al., 2009; Tavirimirwa et al., 2012; Tessema & Baars, 2004; Zewdu et al., 2002). Similarly, the acid detergent fiber (ADF) and neutral detergent fiber (NDF) levels recorded here align with findings by Gemiyo et al. (2017) but are notably higher than those reported in other studies on Napier grass (Zewdu et al., 2002; Tessema & Baars, 2004; Manaye et al., 2009). The elevated ADF and NDF content observed could potentially reduce forage intake and digestibility, as suggested by Van Soest (1995). Specifically, Meissner et al. (1991) established that NDF concentrations exceeding 60% in

tropical grasses may restrict dry matter intake (DMI) in cattle. This suggests that the Napier grass analysed in this study may have NDF levels high enough to limit its effectiveness as an optimal livestock feed.

Results of this study revealed that NO increased, on average, the uptake of P, K, Mg, N and Ca by 1.9, 1.7, 1.5, 1.5 and 1.4-fold, respectively, as compared with the CON (**Table 3.5**). Relative to the CON, the uptake of macronutrients by Napier grass was significantly enhanced when SDN were applied in combination with other soil amendments (fertilizer and/or biochar). For example, treatments that received N and P fertilization (i.e. NFB, NF and FB) consistently resulted in increased DM yield and consequently greater uptake of macronutrients (namely, N, P, K, Mg and Ca) thus highlighting the role of synthetic fertilizers in enhancing plant development and the accessibility of nutrients. Since nutrient uptake is primarily driven by dry matter yield and nutrient concentration (Büchi et al., 2015), the lower amount of nutrient uptake in CON and, to some extent BO, was due to lower dry matter yields and the corresponding low nutrient concentrations. Furthermore, human waste (fecal material and urine) is a good supplier of essential plant nutrients and could have improved nutrient composition and uptake, especially in NFB and NF treatments (Yadav et al., 2010). These observations corroborate Kutu et al. (2011) who also observed enhancement in nutrient availability and uptake following addition of human fecal material and urine solely or in combination. Biochar is known for its effective sorption properties (Wang et al., 2022). The sorption effect of biochar bound nutrients and prevented leaching, which improved the nutrient uptake by plants in NFB. The implications of Napier grass nutrient uptake on livestock production is limited by nutritional quality. Islam, et al. (2024) revealed that proper management would be required in farming of ruminants to enhance milk production and meat quality. Enhancing the nutritive value of Napier grass can lead to more sustainable livestock production systems. This is particularly important in regions where grazing lands are limited, as it allows for increased animal-sourced protein production without relying heavily on external feed inputs (Islam et al., 2024).

The growth cycle also influenced nutrient uptake, with phosphorus (P) and potassium (K) absorption being higher in the second cycle than in the first. Given the initially low soil fertility, this increase in uptake may be attributed to improved soil conditions, particularly nutrient retention over time, which facilitated greater P and K availability. These nutrients are essential for plant growth and root development, contributing to enhanced soil quality and a more

efficient nutrient uptake system as plants mature (Niu et al., 2013; Yawson et al., 2020). Conversely, N and Ca recorded a significantly higher uptake in GC1 compared to GC2. Nitrogen and Ca might have been highly required in GC1 due to nutrient demand at early stages of growth for crop development, hence higher uptake and consequently suffered depletion in GC2. Debruin and Butzen (2014) also documented that nitrogen is rapidly taken up by corn at early due to its high mobility in soil, which is parallel to our observation. Macronutrients are absorbed at similar exchange site; the less absorption of P and K could have reduced nutrient competition and allowed for increased Ca uptake on the vacant sites. Zhang et al. (Zhang et al., 2010) reported a similar phenomenon following a study on K performance in the presence of N.

3.5 Conclusion

The findings indicate that the entrenchment of SDN can be a viable practice for improving DM yield of Napier grass, particularly in areas where soil nutrient levels are low or during dry periods when soil moisture levels are severely low. However, significant responses in terms of fodder productivity were only realized when nappies were entrenched in combination with synthetic N and P fertilizers. Despite positive effects on dry matter production, SDN the nutritional quality of Napier grass did not respond to treatments, particularly in short-term (two growth cycles), which remains a major concern for livestock owners in rural areas. The findings indicate that Napier grass has higher requirements of nutrients that could not be met through entrenching SDN, especially in nutrient-poor soils. Results of the study also highlights the need for variety improvement programs to address low DM accumulation and nutrient content in Napier grass. Programs could involve breeding Napier grass varieties that thrive in nutrient-poor soils, more resilient to drought and capable of producing higher quality fodder that meets the nutritional demands of livestock. Such efforts would be crucial for improving the sustainability and productivity of livestock farming in rural areas. The effects of these treatments on soil quality parameters still needed to be understood.

CHAPTER 4

Soiled Nappies and Biochar as Amendments: Impacts on Moisture Content, Fertility and Microbial Biomass Carbon of a Degraded Soil

(A version of this chapter has been submitted to the Journal of Soil Science and Plant Nutrition)

4.1 Introduction

Soiled nappies are normally landfilled due to the environmental detriment they possess and the complexity of recycling techniques. The urine and faecal matter present in these waste materials contain key nutrients such as nitrogen (N), phosphorus (P), and potassium (K), which can impact soil fertility and plant growth (Kutu et al., 2011). Nitrogen, in particular, is a fundamental component of proteins, amino acids, and nucleic acids, all of which are crucial for plant foliar development and overall growth (Wang et al., 2023). Nitrogen also increases soil organic carbon (SOC) stocks, which largely impacts microbial activity, nutrient cycling and mineralization in soil (Tang et al., 2023). P contributes to seed germination and photosynthesis, which are essential in plant development (Pan et al., 2024). K plays a crucial role in photosynthesis and plant water-use efficiency through stomatal regulation. Nappies are also composed of SAP that absorb and retain huge amounts of moisture. The applicability of SAPs in agriculture has been widely explored (Behera and Mahanwar, 2020, Shahidian et al., 2010, Supare and Mahanwar, 2022) and findings show potential in moisture conservation. Long-term studies on the same subject have further revealed contributions to SOC and microbial activity (Singh et al., 2023).

Land degradation is a prevalent global issue, encompassing about 25% of total land worldwide (Hossain et al., 2020) and responsible for biodiversity depletion. Soil degradation, the major component of land degradation is often characterized by poor soil quality associated with erosion, removal of nutrients, loss of organic matter, microbial activity decline, as well as poor moisture regulation (Gao et al., 2024, Samec et al., 2023, Zaitsev et al., 2022). Loss of organic matter and a defined structure in degraded soils compromises the ability of the soil to regulate

soil moisture and retain nutrients. Low microbial biomass carbon, directly related to organic matter content, inhibits efficient nutrient cycling which further annihilates soil quality. While addressing these issues is critical, sustainability remains imperative.

Proper moisture management is vital for soil productivity and crop growth, particularly in degraded soils where poor water holding capacity prevails (Samec et al., 2023). Improving soil fertility status and microbial biomass carbon also benefits crop production and soil ecosystem, especially the microbial communities responsible for organic matter breakdown and nutrient mineralization. The integrated management of these factors has the potential to reverse soil degradation and contribute positively to mitigating land degradation. This study sought to explore the potential of soiled nappies and *Acacia mearnsii* biochar applied as soil amendments to enhance soil moisture retention, fertility status and microbial biomass carbon. SAPs from nappies were hypothesized to improve soil moisture. Nutrients from human waste were expected to improve soil fertility level and microbial biomass carbon. The sorption capacity of biochar and influence on soil structure and porosity was anticipated to improve nutrient retention and soil water content.

4.2 Methods and materials

4.2.1 Site description, land preparation and materials used in the study

Study site was described in section 3.2.1 while land preparation and source of planting material was provided in section 3.2.3.

4.2.2 Experimental design, application of soil amendments and plant propagation

Experimental design was provided in section 3.2.4, while application of soil amendments was documented in section 3.2.4.1. Plant propagation was detailed in section 3.2.4.2.

4.2.3 Data collection, soil sampling and laboratory analyses

4.2.3.1 Soil moisture monitoring

Soil moisture monitoring took place from 16 February 2023 up to 7 March 2024. The soil moisture was measured at depths of 10 and 20cm using a HydroSense II (Campbell Scientific) water content sensor coupled with CS658 probes. The probes were inserted fully into the soil

within the planted hedgerow. Two soil readings were taken using the probe: a 10cm reading was obtained by inserting the probe at an angle of approximately 45°, and a 20cm reading was obtained by inserting the probe vertically (90^{o} to the soil surface). The nappy moisture was taken from NFB, NF, NB and NO by inserting the probe as done on the 20cm reading. The nappy was reached when the moisture reading drastically increased. While the HydroSense II (Campbell Scientific) could save data, manual recording was also adopted to minimize risk of data losses. The CS658 probes were damaged after 16 March 2023 to 1 June 2023 and hence the missing data.

4.2.3.2 Soil fertility and MBC analysis

For both soil fertility parameters and microbial biomass carbon (MBC), five subsamples were taken per plot and combined to form a composite sample. Soil fertility samples were taken at 0-30 cm depth to coincide with the primary sampling depth in CHAPTER 3 while for MBC, the soil was sampled at 0-20 cm depth. The 0-30cm depth is standard for growth of many crops and therefore a benchmark for soil fertility monitoring while MBC is sensitive at top depths, hence option for 0-20cm.

4.2.3.2.1 Soil fertility status

The five subsamples collected from each plot were merged to form one plot's composite sample, placed in soil sample boxes and sent to laboratories at the Fertiliser Advisory Service of the Department of Agriculture (Cedara) for determination of soil chemical and physical properties.

Soil pH was measured at a 1:2.5 soil to potassium chloride (KCl) solution ratio using a pH meter after shaking at 400 rpm for 5 minutes, followed by a 30-minute standing period. To analyze exchangeable calcium (Ca) and magnesium (Mg), the pH solution was filtered using No. 1 Whatman filter paper. A 5 ml aliquot of the supernatant was then diluted with 20 ml of 0.0356M Strontium Chloride (SrCl2), and the concentrations of Ca and Mg were determined using Atomic Absorption Spectrometry (Varian 2600, California, USA). Extractable acidity was determined by diluting 10 ml of the supernatant with 10 ml of distilled water and adding 4 drops of phenolphthalein, followed by titration with a 0.005M sodium hydroxide (NaOH) solution.

The Ambic-2 extraction method was adopted to determine available phosphorus (P), exchangeable potassium (K), zinc (Zn), copper (Cu), and manganese (Mn). A 2.5 ml aliquot of soil was added to a beaker containing 25 ml of Ambic-2 solution (comprising 0.25 M NH_4CO_3, 0.01 M Na_2EDTA, 0.01 M NH_4F, and 0.05 g L-1 Superfloc (N100), adjusted to pH 8 with concentrated ammonia solution). The suspension was stirred at 400 rpm for 10 minutes, then filtered using Whatman No. 1 filter paper. Available P was determined using a modification of the Murphy and Riley (1962) molybdenum blue method (Hunter, 1974). Atomic Absorption Spectrometry (AAS) was used to analyze exchangeable K (after diluting 5 ml of the filtrate with 20 ml of de-ionized water) and Zn, Cu, and Mn (using the undiluted filtrate)

Soil organic carbon was analysed using the Walkley-Black method (Allison, 1995), which involves oxidizing organic matter with potassium dichromate in a sulfuric acid medium. The excess dichromate was quantified by titration against a standard sulphate solution.

Total carbon (C), nitrogen (N), and sulfur (S) were analyzed using the Automated Dumas dry combustion method with a LECO CNS 2000 (Leco Corporation, Michigan, USA; Matejovic, 1996). In this method, samples were weighed into a ceramic crucible, and 0.5 g of vanadium pentoxide was added as a combustion catalyst to enhance sulfur recovery. The crucible contents were then combusted at 1350°C. The resulting gases were passed through two infrared cells to determine sulfur (as SO2) and carbon (as CO2), while nitrogen (as N2) was measured in a thermal conductivity cell.

4.2.3.2.2 Microbial biomass carbon

Microbial biomass carbon (MBC) samples were placed in labeled, airtight plastic bags and stored in a cooler with ice to preserve microbial activity. MBC was measured using the chloroform fumigation-extraction technique as outlined by Vance et al. (1987). For each sample, 10 g was subjected to fumigation in a vacuum desiccator containing 50 mL of ethanol-free chloroform in a 100 mL beaker, with boiling chips added to facilitate evaporation. The fumigation process lasted 24 hours in a dark room maintained at a constant temperature of 25°C. The desiccator was evacuated with the aid of vacuum pump until chloroform started boiling, after which the tap was sealed. This process was repeated about five (5) times and the desiccator was placed in a dark room for 24 hours. A counterpart unfumigated sample (10g) was placed under the same conditions, except inclusion of chloroform. After 24 hours, the

chloroform was removed and the dedicator was evacuated five (5) times with with a vacuum pump. The soil samples were then transferred to 100ml centrifuge tubes containing 40ml of extractant (0.5M K_2SO_4) as recommended by Joergensen and Olfs (1998) that a ratio must be 1:2 to 1:5 [soil oven-dry mass (g): extractant (ml)]. The contents were shaken at 180 rpm for 60 minutes and filtered to storage bottles using Whatman No. 1 filter paper. Organic carbon (OC) in the extract was analyzed by Walkely-Black dichromate oxidation method using 10ml of extract and 10ml of potassium dichromate. MBC was then determined by the difference between OC in fumigated and unfumigated samples.

$$MBC\ (mg\ kg^{-1}\ soil) = (C_F - C_{UF})/\ k_{EC}$$

Where:

C_F = extractable C in a fumigated sample; C_{UF} = extractable C in an unfumigated sample; k_{EC} = 0.35 is the correction factor for inefficiencies during extraction of MBC (Wu et al. 1990).

4.2.4 Statistical analysis

A one-way ANOVA was conducted using GENSTAT (23rd edition) to evaluate the impact of different treatments on soil moisture, fertility status, and microbial biomass carbon (MBC). Mean comparisons were carried out using Tukey's multiple range test, with statistical significance set at $p < 0.05$.

4.3 Results

4.3.1 Soil moisture

There were significant treatment effects on soil moisture for both depths. Although not consistent for all sampling times, treatments with nappies (NB, NO, NFB) had significantly lower in soil moisture than BO and CON (Figure 4.1). The BO was consistently higher in soil moisture content than NF, except from 30 November 2023 to 7 March 2024 (**Figure 4.1**). Both depths (10cm and 20cm) revealed a similar soil moisture trend throughout the monitoring period. Nappy moisture was not significant among the nappy-supplied treatments but drastically higher than soil moisture (**Figure 4.2**).

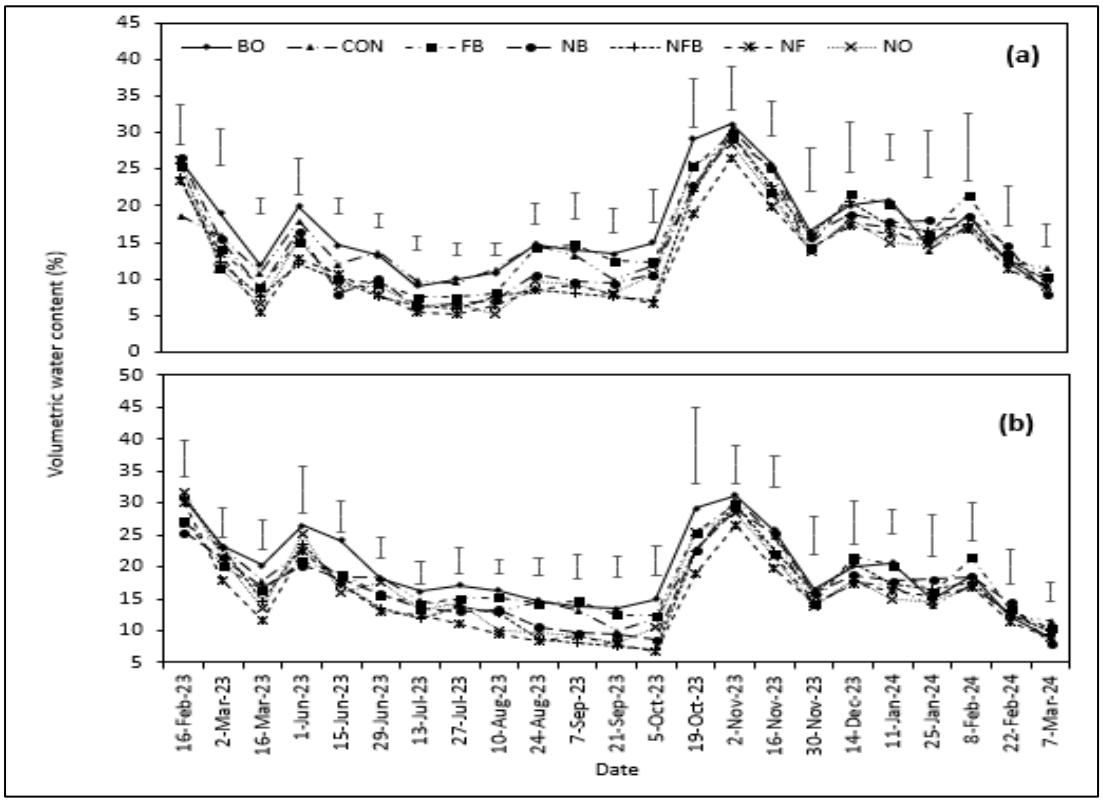


Figure 4.1: Volumetric water content monitored using HS2 device coupled with CS658 probes[1] at (a) 10cm and (b) 20cm depths as affected by seven treatments.

[1] The C658 probes were damaged due to soil compaction after 16 March 2023 up to 1 June 2023, hence the missing data.

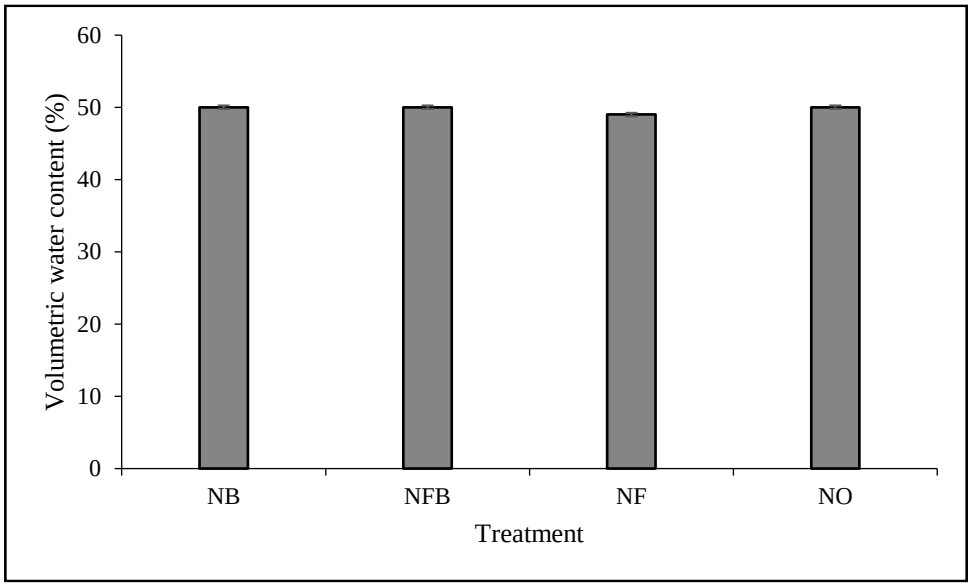


Figure 4.2: Average moisture content recorded from inside the entrenched SDN.

4.3.2 Soil fertility status

A one-way ANOVA revealed a significant treatment effect on total N, exchangeable K and Ca and extractable Mn (**Figure 4.3**). The NFB treatment was persistently the highest in the concentrations of nutrients except for K that was highly accumulated on NF, NO, and NB. The NFB and the NO had higher total N than the CON, NF and FB. Nitrogen in NFB-amended soil increased by 52% in comparison to CON (**Figure 4.3a**). All treatments exhibited significantly higher potassium (K) levels compared to the CON. Among the treatments, NO, NF, and NB showed the highest K levels, with no significant difference among them (**Figure 4.3b**). The NF and BO treatments had a significantly lower exchangeable Ca than the rest of the treatments, while NFB was higher than all the treatments, except for NO, FB and CON (**Figure 4.3c**). In terms of extractable Mn, the NFB and NO treatments had higher extractable Mn than the CON treatment. There were no significant effects on pH, acid saturation, SOC, available P, exchangeable Mg and extractable Cu and Zn (**Table 4.1**).

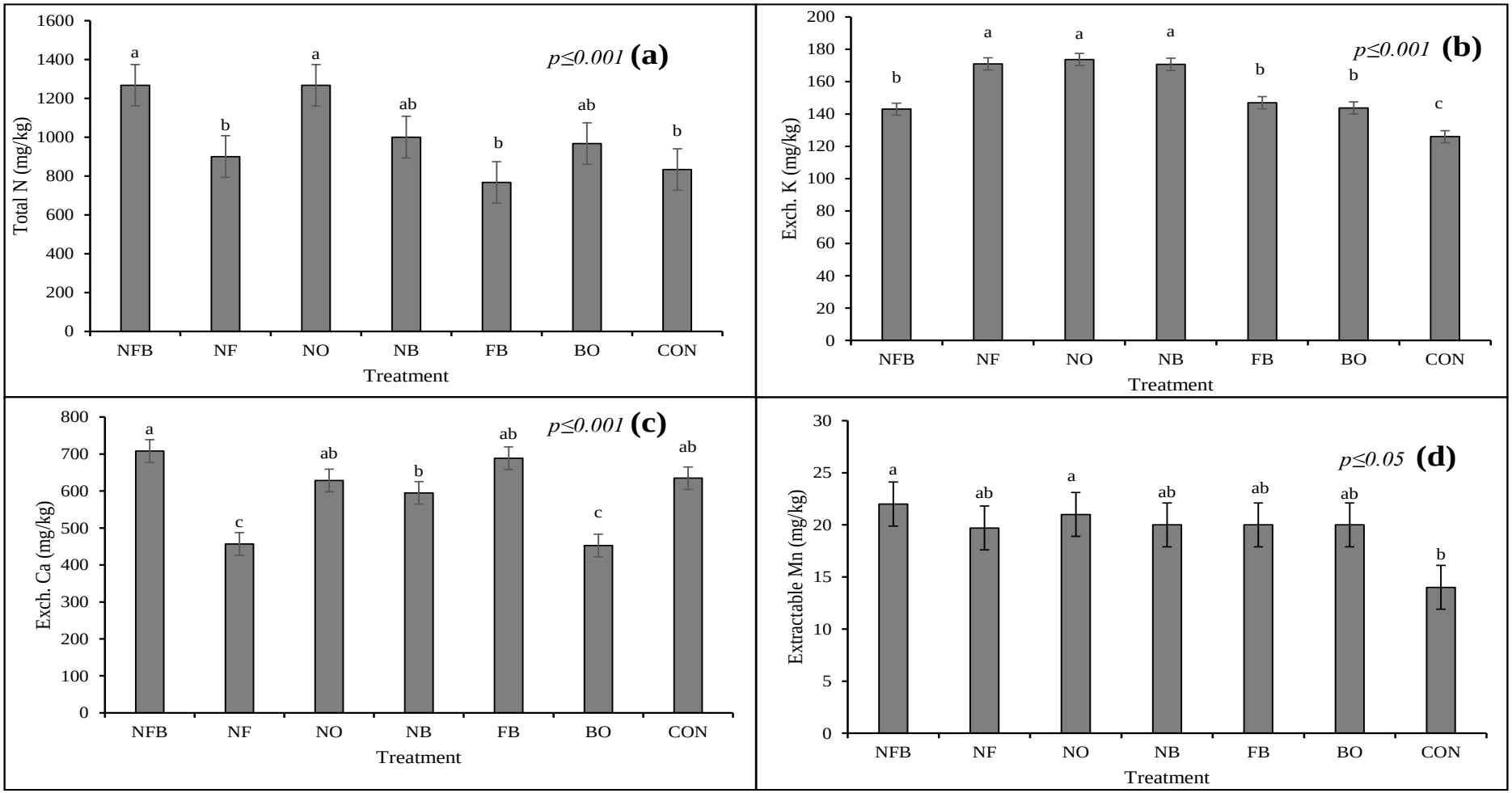


Figure 4.3: A significant response of (a) total N, (b) exchangeable K, (c) exchangeable Ca, and (d) available Mn to seven treatments according to Tukey's LSD

Table 4.1: Selected soil fertility indicators in response to seven treatments at 30cm below soil surface

Soil property	Units	Treatment							*F-statistics*
		NFB	NF	NO	NB	FB	BO	CON	
pH	KCl	4.21±0.08	4.18±0.09	4.27±0.02	4.26±0.02	4.30±0.09	4.22±0.07	4.21±0.05	0.63ns
AS	%	5.00±1.15	8.67±0.88	3.33±0.33	4.33±0.88	4.33±1.86	6.00±2.08	5.67±1.33	2.62ns
SOC	%	1.50±0.12	1.40±0.06	1.77±0.18	1.50±0.21	1.37±0.03	1.40±0.00	1.27±0.15	1.55ns
Total cations	cmol/kg	8.18±0.03	7.36±0.23	7.92±0.33	7.81±0.02	7.96±0.34	7.88±0.26	7.48±0.00	1.80ns
N	mg/kg	1267.0±0.01a	900.0±0.01b	1267.0±0.00a	1000.0±0.00ab	767.0±0.01b	967.0±0.00ab	833.0±0.00b	8.15***
P	mg/kg	2.00±0.58	1.33±0.33	1.33±0.33	1.67±0.67	1.33±0.33	1.67±0.67	1.00±0.00	0.41ns
K	mg/kg	143.0±1.45b	171.0±2.31a	173.7±1.45a	170.7±2.03a	147.0±0.58b	143.7±2.03b	126.0±3.46c	56.59***
Ca	mg/kg	708.0±13.28a	456.7±6.64c	628.3±29.21ab	595.0±23.67b	688.7±12.41ab	452.7±21.07c	634.7±12.88ab	26.97***
Mg	mg/kg	462.0±13.65	456.7±18.76	442.0±5.77	477.7±17.03	523.7±27.42	436.7±69.29	423.7±4.91	1.19ns
Zn	mg/kg	0.53±0.12	0.47±0.07	0.27±0.18	0.23±0.15	0.37±0.09	0.47±0.13	0.27±0.13	0.91ns
Mn	mg/kg	22.0±1.73a	19.7±0.33ab	21.0±0.58a	20.0±1.15ab	20.0±0.58ab	20.0±2.52ab	14.0±0.00b	3.52*
Cu	mg/kg	2.13±0.43	1.70±0.55	1.57±0.26	1.57±0.27	1.43±0.19	1.20±0.12	1.77±0.44	0.97ns

Means within the same column sharing the same letter are not significantly different (P > 0.05) according to Tukey's LSD; ns = not significant

4.3.3 Microbial biomass carbon (MBC)

There was statistical variation ($p<0.001$) among treatments in terms of MBC. All the treatments, except FB, had substantial greater MBC than the CON and BO treatments. The NFB recorded the highest MBC (1162 mg/kg) and was statistically greater than all other treatments, except for NB. (**Figure 4.4**).

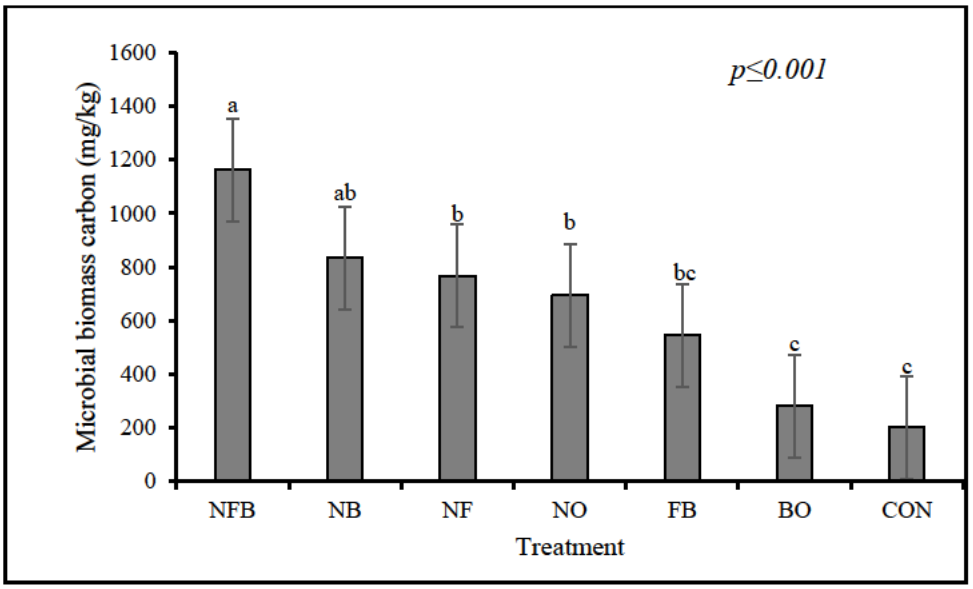


Figure 4.4: Microbial biomass carbon as affected by seven treatments at 0-20cm.

4.4 Discussion

4.4.1 Soil moisture content

The lower soil moisture content displayed by nappy-supplied treatments (NF, NFB, NO, NB) than the CON treatment could be attributed presence of SAP (SAPs), material responsible for liquid absorption in the nappies (**Figure 4.1**). The superabsorbent polymers (SAPs) contain hydrophilic groups, enabling them to absorb and retain up to 100-fold their initial weight in liquid (Bachra et al., 2020, Xu et al., 2024). This capacity, in-part explains lower soil moisture content observed where nappies were supplied in a manner that SAPs swabbed moisture in their vicinity, decreasing moisture in localized soils. Considering that soil moisture was monitored within the planted hedgerow that is proximal to the nappies further accentuates lower soil moisture in the presence of nappies. The finding on **Figure 4.2** underscore this effect through significantly higher moisture inside the nappies, despite having sustained dry winter periods. The higher soil moisture in the control (CON) and the BO treatments can therefore be

attributed to absence of nappies that soak up moisture. The findings of the current study were consistent with those of Shahidian et al. (2010) who observed slightly lower soil moisture following application of SAPs and associated the decline with plant absorption. Nappies also improved DM accumulation, and all nappy-supplied treatments accumulated higher DM yield than CON and BO (Chapter 3; Figure 3.4), which could have increased water consumption, and consequently reducing soil moisture levels on NO, NB, NFB, and NF. In contrast, the results of the present study differ from several studies that have reported improved soil moisture following the application of SAPs (Sánchez-Orozco et al., 2017, Tripathi and Melo, 2020). This could stem from differences in working and environmental conditions between the studies. Once absorbed, SAPs gradually release water, potentially disrupting moisture redistribution and leading to reduced soil moisture in localized areas. Observations of slow water release by SAPs, as reported by Zekry et al. (2020), and those of biomass production in Chapter, provide supporting evidence for this result. Napier grass, with its robust root system improves soil structure and enhance soil moisture retention (Yang et al., 2016). A lack of SAPs on CON ensures that moisture is retained within the soil ecosystem following rootage enhancement. This finding is furthered underscored by Tamta et al. (2023) who observed an increase in moisture retention owing to vigorous Napier grass growth and well-developed rootage. Biochar also improves soil porosity, and structure (Baiamonte et al., 2019). This directly boosts soil moisture holding capacity, hence higher volumetric water content observed on BO.

4.4.2 Soil fertility indicators

The causative mechanisms responsible for release, retention and loss of elements in soil are complex and condition-based. The response of macronutrients to treatment application was significant ($p \leq 0.05$) on N, K, and Ca (Table 4.1). The higher total N observed in nappy-amended treatments, particularly NO (1267mg/kg) and NFB (1267mg/kg) than the CON (833mg/kg) suggested that the presence of nappies increased soil N, which could mineralise and be available for plants. The biodegradable component of nappies acts as an organic input, influencing soil fertility (Bossolani et al., 2023). Decomposition of organic matter from nappies increased total N concentration in soil, hence more N observed on nappy-inclusive treatments. This finding corroborates with Utami et al. (2020), who observed elevated nitrate levels following organic matter breakdown. Soiled nappies could also directly contribute nitrogen

from nutrient-rich urine and faecal material (Kuwornu and Obiri-Danso, 2015). Biochar has a large surface area and improves soil cation exchange capacity, which consequently adsorbs and immobilizes nutrients (Hao et al., 2024), enhancing soil nutrient retention. Low N concentrations observed on FB despite nitrogen supply during fertilization and biochar inclusion, suggests that, while biochar has a mitigative impact on nutrient leaching (Llovet et al., 2022); the amount of total N measured could depend on N added. While the same amount of N was added as fertiliser, treatments with nappies and fertiliser had more initial N. This further underscore contribution of SDN as a stable N source. The similar trends of manganese (Mn) to that of total N could be as result of greater dry matter production, resulting in greater production of organic acids, which may have solubilised the Mn. However, this production of organic acids was not studied.

Calcium was highly concentrated on NFB (708mg/kg), significantly surpassing NB (595mg/kg), NF (457mg/kg) and BO (452mg/kg) (**Table 4.1**). Single superphosphate (SSP) is one of the inorganic inputs applied prior to planting and is composed of mono-calcium phosphate and calcium carbonate dihydrate (Blair, 2008). This directly supplies calcium as a secondary element, increasing Ca levels in soil, hence the observation on NFB. The noted effect on soil Ca accords with the findings of Sarangi et al. (2020) who also reported enhanced levels of calcium following SSP application. Similarly to N, organic matter decomposition from the nappies could have conditioned the soil to favour Ca solubility, further increasing calcium under the influence of NFB. Biochar also contributed to the Ca, from the original feedstock (*A. mearnsii*) hence higher concentrations on NFB. The effect of the combined effect in NFB was supported by the significantly lower exchangeable Ca levels in the NB, BO NF even though each treatment incorporating either nappies or biochar. This observation underscores the efficacy of the synergistic interaction between nappies, fertilizer, and biochar, suggesting that the combination of all three components is more effective than single or dual applications in terms of N and Ca. The significantly higher K concentrations in all the treatments than the CON treatment suggested that the amendments added K to the soil, with the contribution of human excreta in SDN treatments and K from the *A. mearnsii* wood, used to make biochar. Human waste has been widely documented (Kuwornu and Obiri-Danso, 2015, Yadav et al., 2010) to increase nutrient concentrations, including potassium.

4.4.3 Soil microbial biomass carbon (MBC)

The NFB treatment exhibited the highest microbial biomass carbon (MBC) level (1162 mg/kg), whereas the control recorded the lowest (201 mg/kg) (**Figure 4.4**). This increase in MBC under NFB may be attributed to the synergistic effect of nappies, biochar, and fertilizer in enhancing microbial activity. As the most readily available form of carbon, MBC plays a crucial role in short-term nutrient cycling and the decomposition of organic matter (Song et al., 2020). The low MBC in the BO treatment indicated that *A. mearnsii* biochar, on its own, did not increase microbial biomass, possibly as a result of lack of nutrients, especially N (as supported by total N results). Microbes rely on nutrients and labile carbon as energy source, and biochar consists of the stable form of carbon, hence less capacity to affect MBC (Adhikari et al., 2024). However, the biochar prevents nutrient leaching and improves moisture which favour microbial activity. Our findings concur with (Liu et al., 2016) who also discovered no response from MBC following biochar application. Biochar also binds and deactivates nutrients; hence no significant effect was found when it was combined with fertilizer. The significantly higher MBC in the NB treatment than the CON emphasises the importance of nappies in improving microbial activity. Diaper components such as wood pulp and starch are organic and biodegradable, both which are crucial for functionality of the microbes. The coalescence of such favourable conditions induced by nappies and biochar could motivate a varietal difference on MBC. The greatest MBC in the NFB could be explained by favourable conditions created by nappies, biochar and fertiliser (nutrients and moisture) for microbes.

4.5 Conclusion

Nappy-inclusive treatments resulted in a decline in soil moisture, especially in winter during a dry season. The synergistic effect offered by the combination of nappies, fertilizer and biochar significantly improved other soil quality indicators such as soil N, Ca, Mn and MBC. This is because the NFB treatment integrated organic matter and nutrients from soiled nappies, inorganic fertilizer that supplied readily available nutrients and nutrient retention provided by biochar. Potassium concentration was significantly enhanced by the treatment applications, with all treatments showing significantly higher levels than the control (CON). Further studies should focus on monitoring long term effects on nappies, biochar and their combination with

fertilisers on soil moisture, and chemical and biological properties on contrasting soils and climatic conditions.

CHAPTER 5

General Discussion, Conclusions, and Recommendations

5.1 General Discussion

The incorporation of SDN and *Acacia mearnsii* biochar as soil amendments addresses multiple environmental and agricultural critical challenges. This study explored the synergistic effects of these amendments on, Napier grass (*Pennisetum purpureum*) productivity, and health of degraded soils, presenting a promising approach to tackle challenges of nappy waste management, soil degradation encroachment of *A. mearnsii* and fodder shortages. Guided by the findings from the experimental chapters, this discussion highlights the impacts and broader implications of these amendments.

The results consistently demonstrated the effectiveness of nappies, biochar, and their combinations in enhancing Napier grass dry matter (DM) yield. A prominent observation was the contrasting effects of nappies and biochar on soil moisture dynamics. Nappies, due to their superabsorbent polymers, acted as localized moisture sinks, significantly reducing moisture in proximal soils. This finding also suggests that NFB, NF, NB, and FB treatments exhibited enhanced root efficiency, facilitating greater soil moisture uptake and subsequently leading to a more pronounced depletion of soil moisture. The higher DM induced by the nappies could result to soil moisture depletion due to enhanced evapotranspiration in higher DM. In contrast, biochar enhanced soil water retention by improving soil porosity and structure. The biochar-only (BO) treatment maintained the highest soil moisture levels throughout the study, underscoring the efficacy of biochar in optimizing soil water dynamics. The higher soil moisture in the BO and CON are primarily attributed to lower DM and absence of nappies. These findings partly suggest that while nappies provide temporary moisture reserves for plant uptake, their application requires careful management to prevent localized moisture depletion. However, on another viewpoint, the slow-release behaviour of nappy SAP (Zekry et al., 2020) could mean that the retained moisture will act as an accessible sink, benefiting the plants

particularly in a dry season. Regardless, combining nappies with biochar, as seen in NB and NFB treatments, can help stabilize these effects and ensure moisture availability.

The improved uptake of macronutrients promoted dry matter (DM) accumulation in the nappy-amended treatments, especially NFB. This finding highlights the synergistic effect of nappies in enhancing nutrient release and biochar in improving soil structure and nutrient retention (Kutu et al., 2011; Manirakiza et al., 2024). Notably, positive correlations between tiller height, tiller counts, and DM yield further substantiate the influence of amendments on plant growth dynamics. Furthermore, SPAD chlorophyll readings indicated that photosynthetic efficiency (Zhang et al., 2022) was enhanced by improved nutrient availability in amended soils. Though Napier grass biomass production increased, the amendments had less significant effects on forage nutritional quality and chemical composition. This outcome implies that while nappies and biochar enhance soil fertility and growth conditions, supplementary measures may be necessary to ensure an improved forage nutritional quality. For instance, integrating micronutrient-rich fertilizers could enhance the nutritional value of fodder, while organic amendments could assure sustainability, particularly in degraded soils as postulated by Larney and Angers (2012).

The entrenchment of nappies and biochar improved soil fertility and microbial biomass carbon (MBC), which are critical indicators of soil health (Nunes et al., 2020). Treatments inclusive of nappies, particularly when combined with biochar and fertilizer, improved concentrations of some key macronutrients (N, K, and Ca) and enhanced microbial activity. The enhanced soil fertility parameters in some nappy treatments, particularly NFB, suggest that these treatments facilitated nutrient uptake but still concentrated abundant nutrients in soil to influence soil fertility. However, in some treatments, the nutrients in soil were exhausted during uptake to the level of the control, resulting to lower soil concentrations. Biochar's porous structure likely facilitated microbial colonization and nutrient retention, while nappies contributed organic carbon and nutrients to the soil system (Liu et al., 2016, Šimanský et al., 2018). The increased microbial biomass carbon (MBC) observed in treatments like NFB highlights the effectiveness of amendments in reactivating biological activity in abandoned, degraded soils. Enhanced microbial activity is essential for nutrient cycling and the formation of soil organic matter (Wang et al., 2022), both of which are crucial for potential long-term soil rehabilitation.

The recycling of soiled nappies, synergistically with the invasive *Acacia mearnsii* wood for biochar production present prospective efforts to tackling pressing environmental issues. By repurposing indiscriminately disposed nappies and utilizing an invasive species, this approach contributes to pollution control and ecosystem restoration. The integration of these materials in agricultural practices also promotes sustainable land use, particularly in abandoned degraded lands of the rural areas.

5.2 Limitations, Conclusions and Recommendations

In conclusion, this study highlighted the potential of incorporating SDN and biochar derived from black wattle as soil amendments to restore degraded soils and enhance Napier grass productivity. The significant improvements in DM yield and soil fertility, coupled with enhanced microbial activity, emphasize the prospective application of these amendments. The localized soil moisture reduction around nappies may not be a limitation if the plants can access the moisture in the nappies. The efficacy of the "moisture sink" created by nappy-absorbed moisture, to potentially sustain the plants through dry seasons, must be further monitored for validation. Furthermore, the less significant improvements in fodder nutritional quality suggest that farmers may need to integrate supplements if they use the Napier fodder produced as in the current study. Future studies should investigate the long-term impacts of these amendments across various soil types and climates. Studies on low-cost, applicable and sustainable ways to degrade nappy plastic component could also strongly optimize this method. Addressing these gaps will support the sustainable application of this innovative approach to agricultural and environmental challenges.

REFERENCES

(DEA), D. O. E. A. 2018. South African National Land Cover 2018. *In:* (DEA), D. O. E. A. (ed.). South Africa: GeoTerra Image.

(EPA), E. P. A. 2024. *Municipal Solid Waste Landfills* [Online]. Available: https://www.epa.gov/landfills/municipal-solid-waste-landfills [Accessed].

A.O.A.C 1990. *Official Methods of Analysis,* Washington DC, Association of Official Analytical Chemist.

ABDELSALAM, M. I. 2021. Effects of Overgrazing on Rangeland Resources in Semi-arid Areas and Rangel and Management: A review Article. *Agrica,* 10**,** 144-151.

AFFAIRS, D. O. E. 2018. South African National Land Cover 2018.

AGIM, L. C., AHUKAEMERE, M. C., UZOH, I., ONWUDIKE, S. U., OSISI, A. F., IHEM, E. E. & NKWOPARA, U. 2022. Soil degradation and the human condition, including the pandemic, interactions, causes, impacts, control measures and likely future prospects. *Soil science-Emerging technologies, global perspectives and applications.* IntechOpen.

AIN, N. U., HAIDER, F. U., FATIMA, M., HABIBA, Y, Z. & MING, R. 2022. Genetic determinants of biomass in C4 crops: molecular and agronomic approaches to increase biomass for biofuels. . *Frontiers in plant science,* 13**,** 839588.

AISHWARIYA, S. & PRIYANKA, M. 2020. A review on convenience and pollution caused by baby nappies. *Science and Technology Development Journal,* 23**,** 702-704.

ALBANNA, M. 2012. Solid waste management options and their impacts on climate change and human health. *Environmental protection strategies for sustainable development***,** 499-528.

AL-JABARI, M., GHYADAH, R. A. & ALOKELY, R. 2019. Recovery of hydrogel from baby diaper wastes and its application for enhancing soil irrigation management. *Journal of Environmental Management***,** 255–261.

ANSAH, T., OSAFO, E. L. K. & HANSEN, H. H. 2010. Herbage yield and chemical composition of four varieties of Napier

ASWANIMIYUNI, A., MOHAMAD NOOR, I., HARYANI, H., NORFADZRIN, F. & NURZILLAH, M. 2018. A comparison of feed intake and growth performance of goats fed Guinea grass and Napier grass. *MALAYSIAN JOURNAL OF VETERINARY RESEARCH,* 9**,** 13-18.

AULAKH, M. S. & SIDHU, G. S. Soil degradation in India: Causes, major threats, and management options. MARCO symposium, 2015. 151-156.

AYALEW, S. & MULUALEM, G. 2018. A review on bush encroachment effect on cattle rearing in rangelands. *Journal of Rangeland Science,,* 8**,** 403-415.

BACHRA, Y., GROULI, A., DAMIRI, F., BENNAMARA, A. & BERRADA, M. 2020. A new approach for assessing the absorption of disposable baby diapers and superabsorbent polymers: A comparative study. *Results in Materials,* 8**,** 100156.

BAIAMONTE, G., CRESCIMANNO, G., PARRINO, F. & DE PASQUALE, C. 2019. Effect of biochar on the physical and structural properties of a sandy soil. *Catena,* 175**,** 294-303.

BARROS, T. V., DC CARREGOSA, J., WISNIEWSKI JR, A., FREITAS, A. C., GUIRARDELLO, R., FERREIRA-PINTO, L., BONFIM-ROCHA, L., JEGATHEESAN, V. & CARDOZO-FILHO, L. 2022. Assessment of black liquor hydrothermal treatment under sub-and supercritical conditions: Products distribution and economic perspectives. *Chemosphere,* 286**,** 131776.

BATEMAN, A. M. & MUÑOZ-ROJAS, M. 2019. Chapter One - To whom the burden of soil degradation and management concerns. *Advances in Chemical Pollution, Environmental Management and Protection,* 4**,** 1-22.

BEHERA, S. & MAHANWAR, P. A. 2020. Superabsorbent polymers in agriculture and other applications: A review. *Polymer-Plastics Technology and Materials,* 59**,** 341-356.

BEKUZAROVA, S., BURDZIEVA, O., ARKHIREEVA, I. & DZOBELOVA, L. Soil degradation and remediation. IOP Conference Series: Materials Science and Engineering, 2020. IOP Publishing, 052054.

BLAIR, G. SSP: Single superphosphate, a scenario slowly passing. Proceedings of the 14th Australian Agronomy Conference, Adelaide, South Australia'.(Ed. MJ Unkovich)(Australian Society of Agronomy): http://www. regional. org. au/au/asa/2008/concurrent/plant_nutrition/5950_blairg. htm, 2008. Citeseer.

BORRELLI, P., ROBINSON, D. A., FLEISCHER, L. R., LUGATO, E., BALLABIO, C., ALEWELL, C., MEUSBURGER, K., MODUGNO, S., SCHÜTT, B. & FERRO, V. 2017. An assessment of the global impact of 21st century land use change on soil erosion. *Nature communications,* 8**,** 1-13.

BOSSOLANI, J. W., LEITE, M. F., MOMESSO, L., TEN BERGE, H., BLOEM, J. & KURAMAE, E. E. 2023. Nitrogen input on organic amendments alters the pattern of soil–microbe-plant co-dependence. *Science of the Total Environment,* 890**,** 164347.

BROCK, C., OBERHOLZER, H. R. & FRANKO, U. 2017. Soil organic matter balance as a practical tool for environmental impact assessment and management support in arable farming. Wiley Online Library.

BÜCHI, L., GEBHARD, C. A., LIEBISCH, F., SINAJ, S., RAMSEIER, H. & CHARLES, R. 2015. Accumulation of biologically fixed nitrogen by legumes cultivated as cover crops in Switzerland. *Plant and Soil***,** 163-175.

BUNNING, S., MCDONAGH, J. & RIOUX, J. 2016. Land Degradation Assessment in Drylands: Manual for Local Level Assessment of Land Degradation and Sustainable Land Management.: FAO.

BURGEON, V., FOUCHÉ, J., GARRÉ, S., DEHKORDI, R. H., COLINET, G. & CORNELIS, J.-T. 2022. Young and century-old biochars strongly affect nutrient cycling in a temperate agroecosystem. *Agriculture, Ecosystems & Environment,* 328**,** 107847.

CASTRILLON, N., ECHEVERRIA, M., FU, H., ROY, A. & TOOMBS, J. 2019. Super absorbent polymer replacement for disposable baby nappies. *Commodity Polymer Project. Berkeley: University of California*.

CENCI, F. B., LOUVANDINI, H., MCMANUS, C. M., DELL'PORTO, A., COSTA, D., ARAÚJO, S. D., MINHO, A. & ABDALLA, A. L. 2007. Effects of condensed tannin from *Acacia mearnsii* on sheep infected naturally with gastrointestinal helminthes. *Veterinary Parasitology,* 144**,** 132-137.

CHAN, J. M., DAY, P., FEELY, J., THOMPSON, R., LITTLE, K. M. & NORRIS, C. H. 2015. *Acacia mearnsii* industry overview: current status, key research and development issues. *Southern Forests: a Journal of Forest Science,* 77**,** 19-30.

CHENG, T., LI, R., KOU, X. & WANG, S. 2017. Influence of controlled atmosphere on thermal inactivation of Escherichia coli ATCC 25922 in almond powder. *Food microbiology,* 64**,** 186-194.

CHO, J. Y., YOON, Y.-E., CHOE, H., GODAGEDARA, L. T., LEE, K.-A., KIM, S. C., KIM, Y.-N. & LEE, Y. B. 2024. Influences of continuous wood-derived biochar application on soil chemical properties and lettuce (Lactuca sativa L.) yield. *한국토양비료학회지,* 57**,** 96-105.

COGTA 2020. FINAL IDP 2020/21: DR NKOSAZANA DLAMINI ZUMA LOCAL MUNICIPALITY. *In:* AFFAIRS, D. O. C. G. A. T. (ed.). Pretoria: https://www.cogta.gov.za/.

COLDEBELLA, R., GIESBRECHT, B. M., PEDRAZZI, C., MACHADO, P. F. D. S., COSTA, H. W. D., VIVIAN, M. A., DENARDI, L. & GOMES, C. M. 2023. Anatomical characterization of black wattle wood for the pulp and paper production. *Ciência Rural,* 53**,** e20210865.

COSTA, E. D. S., RIBIERO, C., SILVA, T., RIBEIRO, R., VIEIRA, J., LIMA, A. D. O., BARBOSA, A., DA SILVA JÚNIOR, J., BEZERRA, L. & OLIVEIRA, R. 2021. Intake, nutrient digestibility, nitrogen balance, serum metabolites and growth

performance of lambs supplemented with *Acacia mearnsii* condensed tannin extract. *Animal Feed Science and Technology,* 272**,** 114744.

DEBRUIN, J. & BUTZEN, S. 2014. Nitrogen Uptake in Corn. *Crop Insights,* 24**,** 1-6.

DESSÌ, L., PODDA, L., BRUNDU, G., LOZANO, V., CARROUÉE, A., MARCHANTE, E., MARCHANTE, H., PETIT, Y., PORCEDDU, M. & BACCHETTA, G. 2021. Seed germination ecophysiology of Acacia dealbata Link and *Acacia mearnsii* De wild.: two invasive species in the Mediterranean basin. *Sustainability,* 13**,** 11588.

DLAMINI, P., CHIVENGE, P., MANSON, A. & CHAPLOT, V. 2014. Land degradation impact on soil organic carbon and nitrogen stocks of sub-tropical humid grasslands in South Africa. *Geoderma,* 235**,** 372-381.

DOKBUA, B., WARAMIT, N., CHAUGOOL, J. & THONGIOO, C. 2021. Biomass Productivity, Developmental Morphology, and Nutrient Removal Rate of Hybrid Napier Grass (Pennisetum purpureum x Pennisetum americanum) in Response to Potassium and Nitrogen Fertilization in a Multiple-Harvest System. *BioEnergy Research***,** 1-12.

EBHUOMA, O., GEBRESLASIE, M., EBHUOMA, E., LEONARD, L., SILAS NGETAR, N. & ZAMISA, B. 2023. Farmers' perception of soil erosion and degradation and their effects on rural livelihoods in KwaMaye Community, KwaZulu-Natal, South Africa. *Journal of Asian and African Studies,* 58**,** 1405-1421.

ENDALE, T., DIELS, J., TSEGAYE, D., KASSAYE, A., BELAYNEH, L. & VERDOODT, A. 2023. Farmer-science-based soil degradation metrics guide prioritization of catchment-tailored control measures. *Environmental Development,* 45**,** 100783.

ESPINOSA-VALDEMAR, R. M., SOTELO-NAVARRO, P. X., QUECGOLAC-PIÑA, GARCÍA-RIVERA, M. A., BELTRÁN-VILLAVICENCIO, M., OJEDA-BENÍTEZ, S. & VÁZQUEZ-MORILLAS 2014. Biological recycling of used baby nappies in a small-scale composting system. *Resources, Conservation and Recycling,* 87**,** 153-154.

FEBO, P. & GAGLIARDINI, A. 2018. Febo, Pietro, and Alessandro Gagliardini. "Baby Nappies Past and Present: A Critical Review. *Bionanotechnology to Save the Environment***,** 227.

FENG, S., ZHAO, W., ZHAN, T., YAN, Y. & PEREIRA, P. 2022. Land degradation neutrality: A review of progress and perspectives. *Ecological indicators,* 144**,** 109530.

FERRONATO, N., NOVA-PINEDO, M. & TORRETTA, V. 2020. Assessment of Used Baby Nappies Composting in Bolivia. *Sustainability,* 12**,** 5055.

FORRESTER, D. I., BAUHUS, J. & KHANNA, P. K. 2004. Growth dynamics in a mixed-species plantation of Eucalyptus globulus and *Acacia mearnsii*. *Forest Ecology and management,* 193**,** 81-95.

FORRESTER, D. I., SCHORTEMEYER, M., STOCK, W. D., BAUHUS, J., KHANNA, P. K. & COWIE, A. L. 2007. Assessing nitrogen fixation in mixed-and single-species plantations of Eucalyptus globulus and *Acacia mearnsii*. *Tree Physiology,* 27**,** 1319-1328.

FRUERGAARD, T., CHRISTENSEN, T. H. & ASTRUP, T. 2010. Energy recovery from waste incineration: Assessing the importance of district heating networks. *Waste Management,* 30**,** 1264-1272.

GALATOWITSCH, S. & RICHARDSON, D. M. 2005. Riparian scrub recovery after clearing of invasive alien trees in headwater streams of the Western Cape, South Africa. *Biological Conservation,* 122**,** 509-521.

GAO, M., LI, M., WANG, S. & LU, X. 2024. Land Degradation Affects Soil Microbial Properties, Organic Matter Composition, and Maize Yield. *Agronomy,* 14**,** 1348.

GAO, S., HOFFMAN-KRULL, K., BIDWELL, A. & DELUCA, T. H. 2016. Locally produced wood biochar increases nutrient retention and availability in agricultural soils of the San Juan Islands, USA. *Agriculture, Ecosystems & Environment,* 233**,** 43-54.

GBETIBOUO, G. A., RINGLER, C. & HASSAN, R. Vulnerability of the South African farming sector to climate change and variability: An indicator approach. Natural resources forum, 2010. Wiley Online Library, 175-187.

GEMIYO, D., JIMMA, A., & WOLDE, S 2017. Biomass yield and nutritive value of ten Napier grass (Pennisetum purpureum) genotypes at Areka, Southern Ethiopia. *World Journal of Agricultural Sciences,* 13**,** 185-190.

GIBBS, H. & SALMON, J. M. 2015. Mapping the world's degraded lands. *Applied geography,* 57**,** 12-21.

GIESBRECHT, B. M., COLDEBELLA, R., GENTIL, M., NUNES, G. R. S., FINGER, M. R., JARDIM, J. M., PEDRAZZI, C. & CARDOSO, G. V. 2022. The performance of *Acacia mearnsii* De Wild for kraft pulping. *Ciência Florestal,* 32**,** 266-286.

GODFREY, L. & OELOFSE, S. 2017. Historical review of waste management and recycling in South Africa. *Resources,* 6**,** 57.

GOULD, R. 2014. *Disposable Diaper Waste Treatment Options for Israel.* University of Haifa (Israel).

GOVENDER, P. 2007. Status of seedling establishment pests of *Acacia mearnsii* De Wild.(Mimosaceae) in South Africa. *South African Journal of Science,* 103**,** 141-147.

HALIM, R., SHAMPAZURAINI, S. & IDRIS, A. 2013. Yield and nutritive quality of nine Napier grass varieties in Malaysia.

HAN, L., LU, C., CHEN, L., WANG, F., GAO, K., YU, Y. & XU, C. 2024. Carbon sequestration potential of biochar in soil from the perspective of organic carbon structural modification. *Applied Soil Ecology,* 198**,** 105389.

HAO, J., ZHANG, X., ZONG, S., ZHUO, Y., ZHANG, Y., WANG, S., DENG, Y., ZHANG, X. & LI, J. 2024. Biochar as a highly efficient adsorption carrier for sewage sludge-derived nutrients and biostimulants: component fixation and mechanism. *Biochar,* 6**,** 42.

HIRSH, S. 2022. *Are Nappies Biodegradable? Here Are the Most Sustainable Diaper Options* [Online]. Green Matters. Available: https://www.greenmatters.com/p/are-nappies-biodegradable-compostable [Accessed].

HOFFMANN, B. S., DE SIMONE MORAIS, J. & TEODORO, P. F. 2020. Life cycle assessment of innovative circular business models for modern cloth nappies. *Journal of cleaner production,* 249**,** 119364.

HOFFMANN, R. B., DO CARMO, D. L., SILVA, J. R. M., DA TRINDADE, T. P., SANTOS, N. T., DE SÁ MENDONÇA, E. & FERNANDES, R. B. A. 2024. Restoring degraded lands: the role of sewage sludge in modulating soil carbon and nitrogen dynamics. *OBSERVATÓRIO DE LA ECONOMÍA LATINOAMERICANA,* 22**,** e7217-e7217.

HOSSAIN, A., KRUPNIK, T. J., TIMSINA, J., MAHBOOB, M. G., CHAKI, A. K., FAROOQ, M., BHATT, R., FAHAD, S. & HASANUZZAMAN, M. 2020. Agricultural land degradation: processes and problems undermining future food security. *Environment, climate, plant and vegetation growth.* Springer.

HU, Y. K., LIU, X. Y., HE, N. P., PAN, X., LONG, S. Y., LI, W., ZHANG, M. Y. & CUI, L. J. 2021. Global patterns in leaf stoichiometry across coastal wetlands. *Global Ecology and Biogeography,* 30**,** 852-869.

HUO, C., GUO, L., WU, W., YANG, R., ZHAO, Y., LEI, M., SHI, L. & YU, B. 2022. Groundwater Risk Assessment of a Rock Cave Type Landfill with Nontraditional Solid Waste. *Advances in Civil Engineering,* 2022**,** 3675169.

IMPSON, F. 2005. Biological control of Acacia cyclops in South Africa: the role of an introduced seed-feeding weevil, Melanterius servulus (Coleoptera: Curculionidae), together with indigenous seed-sucking bugs and birds.

IMPSON, F., KLEINJAN, C. & HOFFMANN, J. 2021. Suppression of seed production as a long-term strategy in weed biological control: the combined impact of two biocontrol agents on *Acacia mearnsii* in South Africa. *Biological Control,* 154**,** 104503.

INDUMATHI, T. R. & DIVYA, R. 2021. Development of microfibril absorbent substantial for hygiene products using compostable agro-residuals. *Journal of Fiber Science and Technology,* 77**,** 307.

ISHII, Y., HAMANO, K., KANG, D. J., KANNIKA, R., IDOTA, S., FUKUYAMA, K. & NISHIWAKI, A. 2013. C4-Napier grass cultivation for cadmium phytoremediation activity and organic livestock farming in Kyushu, Japan. *Journal of Agricultural Science and Technology. A,* 3**,** 321.

ISLAM, M. R., GARCIA, S. C., ISLAM, M. A., BASHAR, M. K., ROY, A., ROY, B. K., SARKER, N. R. & CLARK, C. E. F. 2024. Ruminant Production from Napier Grass (Pennisetum purpureum Schum): A Review. *Animals,* 14**,** 467.

ISLAM, M. R., GARCIA, S. C., SARKER, N. R., ISLAM, M. A. & CLARK, C. E. 2023. Napier grass (Pennisetum purpureum Schum) management strategies for dairy and meat production in the tropics and subtropics: Yield and nutritive value. *Frontiers in Plant Science,* 14**,** 1269976.

ISLAM, M. T., SULTANA, A. I., CHAMBERS, C., SAHA, S., SAHA, N., KIRTANIA, K. & REZA, M. T. 2022. Recent progress on emerging applications of hydrochar. *Energies,* 15**,** 9340.

ISMAEILIMOGHADAM, S., SHEIKH, M., TAHERI, P., RESALATI, H., JONOOBI, M., AZIMI, B. & S, D. 2022. Manufacturing of fluff pulp using different pulp sources and bentonite on an industrial scale for absorbent hygienic products. *Molecules,* 27**,** 5022.

ISSAKA, S. & ASHRAF, M. A. 2017. Impact of soil erosion and degradation on water quality: a review. *Geology, Ecology, and Landscapes,* 1**,** 1-11.

ITSUBO, N., WADA, M., IMAI, S., MYOGA, A., MAKINO, N. & SHOBATAKE, K. 2020. Life cycle assessment of the closed-loop recycling of used disposable nappies. *Resources,* 9**,** 34.

JIE, C., JING-ZHANG, C., MAN-ZHI, T. & ZI-TONG, G. 2002. Soil degradation: a global problem endangering sustainable development. *Journal of Geographical Sciences,* 12**,** 243-252.

JOHNSON, M. 2020. What's in a Pampers Diaper? *Diapering* [Online]. [Accessed 15/02/2024 2024].

KAKONKE, G., TESFAYE, T., SITHOLE, B. B. & NTUNKA, M. 2019. Review on the manufacturing and properties of nonwoven superabsorbent core fabrics used in disposable nappies. *International Journal of Chemical Sciences,* 17**,** 1.

KALINA, M., MAKWETU, N. & TILLEY, E. 2003. "The rich will always be able to dispose of their waste": a view from the frontlines of municipal failure in Makhanda, South Africa. *Environment Development and Sustainability,* 26**,** 17759–17782.

KAMANZI, M. A. M., C., . ., 44, PP. 2012. Feed inventory and smallholder farmers' perceived causes of feed shortage for dairy cattle in Gisagara District, Rwanda. *Tropical Animal Health and Production,* 44**,** 1459-1468.

KAMEYAMA, K., MIYAMOTO, T. & IWATA, Y. 2019. The preliminary study of water-retention related properties of biochar produced from various feedstock at different pyrolysis temperatures. *Materials,* 12**,** 1732.

KESHAVARZ, L. & FARAHBAKHSH, H. 2012. Effect of superabsorbent on physio-morphological traits and forage yield of millet (Pennisetum Amercanum L.) under different irrigation treatments. *International Journal of Plant, Animal and Environmental Sciences,* 2**,** 149-156.

KGAPHOLA, M. J., RAMOELO, A., ODINDI, J., MWENGE KAHINDA, J.-M., SEETAL, A. R. & MUSVOTO, C. 2023. Impact of land use and land cover change on land degradation in rural semi-arid South Africa: Case of the Greater Sekhukhune District Municipality. *Environmental Monitoring and Assessment,* 195**,** 710.

KHANYILE, A., CAWS, G. C., NKOMO, S. P. L. & MKHIZE, N. M. 2020. Characterisation study of various disposable diaper brands. *Sustainability,* 12**,** 10437.

KHOO, S. C., PHANG, X., NG, C., LIM, K., LAM, S. & MA, N. 2019. Recent technologies for treatment and recycling of used disposable baby nappies. *Process Safety and Environmental Protection,* 123**,** 116-129.

KIM, K.-S. & KIM, K. J. 2018. Evaluation of a disposable-diaper collection trial in Korea through comparison with an absorbent-hygiene-product collection trial in Scotland. *Sustainability,* 10**,** 773.

KIMANI, E. W., MUCHIRI, J. & MAKINDI, S. 2015. Soiled nappies disposal practices among caregivers in poor and middle income urban settings.

KLAHAN, R., KRAJABTHONG, K., MAKSIRI, W., TAMRUANGIT, J., WHANGCHAI, N., PIMPIMOL, T. & WHANGCHAI, K. 2024. The influence of napier grass biomass mixed feed on the biorefinery indicator for Nile tilapia production. *Biomass Conversion and Biorefinery,* 14**,** 1251-1260.

KURIA, A. N. 2015. *Evaluation of tanning strength and quality of leathers produced by selected vegetable tanning materials from Laikipia County, kenya.* University of Nairobi.

KUTU, F. R., MUCHAONYERWA, P. & MNKENI, P. N. 2011. Complementary nutrient effects of separately collected human faeces and urine on the yield and nutrient uptake of spinach (Spinacia oleracea). *Waste management & research,* 29**,** 532-539.

KUWORNU, A. L. & OBIRI-DANSO, K. 2015. Assessment of NPK in human male and female Urine for its fertilising potential in agriculture. *International Journal of Scientific & Technology Research,* 4**,** 160-168.

LAL, R. 2015. Restoring soil quality to mitigate soil degradation. *Sustainability,* 7**,** 5875-5895.

LARNEY, F. J. & ANGERS, D. A. 2012. The role of organic amendments in soil reclamation: A review. *Canadian Journal of Soil Science,* 92**,** 19-38.

LE ROUX, J. & SMITH, H. 2014. *Soil erosion in South Africa - its nature and distribution* [Online]. Pretoria: Grain SA. Available: https://www.grainsa.co.za/soil-erosion-in-south-africa---its-nature-and-distribution [Accessed 4 January 2025].

LE ROUX, J. J., BROWN, G. K., BYRNE, M., NDLOVU, J., RICHARDSON, D. M., THOMPSON, G. D. & WILSON, J. R. 2011. Phylogeographic consequences of different introduction histories of invasive Australian Acacia species and Paraserianthes lophantha (Fabaceae) in South Africa. *Diversity and Distributions,* 17**,** 861-871.

LEE, T.-J., CHOI, D.-C., NAM, Y.-S., JO, J.-H., LEE, H.-S. & RYU, J.-Y. 2015. Studies on the Pulping Conditions of Separating Useful Components from Disposable Diaper Waste. *Journal of Korea technical Association of the Pulp and Paper Industry,* 47**,** 1-8.

LEURS, F. 2021. *Mechanical Recycling of Diaper Plastic Waste.* Master, Eindhoven University of Technology.

LIM, J. K., MÜLLER, J., MAHDI, F. N., CHEN, S. K., TAN, K. B. & LEE, O. J. 2022. New open-loop recycling approaches for disposable diaper waste. *Environmental Reviews,* 30**,** 268-279.

LIU, S., ZHANG, Y., ZONG, Y., HU, Z., WU, S., ZHOU, J. I. E., JIN, Y. & ZOU, J. 2016. Response of soil carbon dioxide fluxes, soil organic carbon and microbial biomass carbon to biochar amendment: a meta-analysis. *Gcb Bioenergy,* 8**,** 392-406.

LLOVET, A., VIDAL-DURÀ, A., ALCAÑIZ, J. M., RIBAS, A. & DOMENE, X. 2022. Biochar addition to organo-mineral fertilisers delays nutrient leaching and enhances barley nutrient content. *Archives of Agronomy and Soil Science,* 69**,** 2537-2551.

LUSIZI, Z., MOTSI, H., NYAMBO, P. & ELEPHANT, D. 2024. Black (*Acacia mearnsii*) and silver wattle (Acacia dealbata) invasive tree species impact on soil physicochemical properties in South Africa: A systematic literature review. *Heliyon*.

MADIBE, R. J. 2021. *Determining the impact of a piggery on the Inhlavini and uMkhomazi Rivers, KwaZulu-Natal.* North-West University (South Africa).

MAKARICHI, L., JUTIDAMRONGPHAN, W. & TECHATO, K. A. 2018. The evolution of waste-to-energy incineration: A review. *Renewable and Sustainable Energy Reviews,* 91**,** 812-821.

MAKAYA, N., DUBE, T., SEUTLOALI, K., SHOKO, C., MUTANGA, O. & MASOCHA, M. 2019. Geospatial assessment of soil erosion vulnerability in the upper uMgeni catchment in KwaZulu Natal, South Africa. *Physics and Chemistry of the Earth, Parts A/B/C,* 112**,** 50-57.

MALEKO, D., MWILAWA, A., MSALYA, G., PASAPE, L. & MTEI, K. 2019a. Forage growth, yield and nutritional characteristics of four varieties of napier grass (Pennisetum purpureum Schumach) in the west Usambara highlands, Tanzania. *Scientific African,* 6**,** 00214.

MALEKO, D., MWILAWA, A., MSALYA, G., PASAPE, L. & MTEI, K. 2019b. Forage growth, yield and nutritional characteristics of four varieties of napier grass (Pennisetum purpureum Schumach) in the west Usambara highlands, Tanzania. *Scientific African,* 6**,** 00214.

MAMAGHANI, Z. G., HAWBOLDT, K. A., MACQUARRIE, S. & KATZ, M. J. 2024. Wood biochar as a point source CO2 adsorbent-impact of humidity on performance. *Fuel,* 361**,** 130737.

MANAYE, T., TOLERA, A. & ZEWDU, T. 2009. Feed intake, digestibility and body weight gain of sheep fed Napier grass mixed with different levels of Sesbania sesban. *Livestock Science,* 122**,** 24-29.

MANI, S., OSBORNE, C. P. & CLEAVER, F. 2021. Land degradation in South Africa: Justice and climate change in tension. *People and Nature,* 3**,** 978-989.

MANI, S., OSBORNE, C. P. & CLEAVER, F. 2021. Land degradation in South Africa: Justice and climate change in tension. *People and Nature,* 3**,** 978-989.

MANIRAKIZA, E., GAGNON, B. & ZIADI, N. 2024. Soil and plant cations as affected by application of wood ash, biochar, and papermill biosolids. *Agronomy Journal*.

MANJORO, M., KAKEMBO, V. & ROWNTREE, K. M. 2012. Trends in soil erosion and woody shrub encroachment in Ngqushwa District, Eastern Cape Province, South Africa. *Environmental management,* 49**,** 570-579.

MANSON, A. D. & ROBERTS, V. G. 2000. Analytical methods used by the soil fertility and analytical services section. *Republic of South Africa, Pietermaritzburg*.

MARTIN, A., HUBBE, A. Y., JESSE, S. D., RICHARD, A. V. & JOEL, J. P. 2013. Enhanced Absorbent Products Incorporating Celluloseand Its Derivatives: A Review. *BioResources,* 6**,** 6622.

MASOUMI, S., BORUGADDA, V. B., NANDA, S. & DALAI, A. K. 2021. Hydrochar: a review on its production technologies and applications. *Catalysts,* 11**,** 939.

MBOKAZI, M. S. & LEBELOANE, L. D. M. 2024. The Danger of Mismanaging Disposable Baby Nappies in Residential Environments: A Case Study of Dukuduku Area. *Journal of Economic Development, Environment and People,* 13**,** 77-86.

MEARNSII DEWILD, A. 2003. *Acacia mearnsii*. *Artículo de internet http://www. scientificlib. com/en/Biology/Plants/Magnoliophyta/AcaciaMearnsii01. ht ml [página consultada el 4 de enero de 2018]*.

MELO, W., DELARICA, D., GUEDES, A., LAVEZZO, L., DONHA, R., DE ARAÚJO, A., DE MELO, G. & MACEDO, F. 2018. Ten years of application of sewage sludge on tropical soil. A balance sheet on agricultural crops and environmental quality. *Science of the total environment,* 643**,** 1493-1501.

MENDOZA, J. M. F., D'APONTE, F., GUALTIERI, D. & AZAPAGIC, A. 2019a. Disposable baby nappies: Life cycle costs, eco-efficiency and circular economy. *Journal of cleaner production,* 211**,** 455-467.

MENDOZA, J. M. F., POPA, S. A., D'APONTE, F., GUALTIERI, D. & AZAPAGIC, A. 2019b. Improving resource efficiency and environmental impacts through novel design and manufacturing of disposable baby nappies. *Journal of Cleaner Production,* 210**,** 917.

MEZZOMO, R., PIVETA, G., LAZAROTTO, M., WALKER, C., MACIEL, C. G., MUNIZ, M. F. & ARAUJO, M. M. 2019. Biological Control of Ceratocystis fimbriata by Bacillus subtilis on *Acacia mearnsii* Seedlings. *Floresta e Ambiente,* 26**,** e20160195.

MIRABELLA, N., CASTELLANI, V. & SALA, S. 2013. Life cycle assessment of bio-based products: a disposable diaper case study. *The International Journal of Life Cycle Assessment* 18**,** 1036-1047.

MOSLEMI, Z., HABIBI, D., ASGHARZADEH, A., ARDAKANI, M. R., MOHAMMADI, A. & SAKARI, A. 2011. Effects of super absorbent polymer and plant growth promoting rhizobacteria on yield and yield components of maize under drought stress and normal conditions. *African Journal of Agricultural Research,* 6**,** 4471-4476.

MOTHER-EASE. 2021. *All in One Versus All in Two Cloth Nappies* [Online]. Mother-ease cloth nappies. Available: https://mother-ease.com/en-ca/blogs/bump-bottom-beyond/all-in-one-vs-all-in-two [Accessed].

MSANGI, J. P. 2007. Land degradation management in Southern Africa. *Climate and land degradation.* Springer.

MTHEMBU, B. E., EVERSON, T. M. & EVERSON, C. S. 2017. Intercropping maize (Zea mays L.) with lablab (Lablab purpureus L.) for sustainable fodder production and quality in smallholder rural farming systems in South Africa. *Agroecology and Sustainable Food Systems,* 42**,** 362–382.

MUDAU, L. S., THUMBATHI, A. M. D. & NKOSI, D. V. 2023a. Poor Disposal of Soiled Nappies in Sub-Saharan Africa: A Gap in Environmental Health Literacy in Rural Communities. *Environmental Health Literacy Update - New Evidence, Methodologies and Perspectives*.

MUDAU, L. S., THUMBATHI, A. M. D. & NKOSI, D. V. 2023b. Poor Disposal of Soiled Nappies in Sub-Saharan Africa: A Gap in Environmental Health Literacy in Rural Communities. *Environmental Health Literacy Update - New Perspectives, Methodologies and Evidence*.

MUKHERJEE, A., GAURAV, A. K., SINGH, S., CHOUHAN, G. K., KUMAR, A. & DAS, S. 2019. Role of potassium (K) solubilising microbes (KSM) in growth and induction of resistance against biotic and abiotic stress in plant: a book review. *Climate Change and Environmental Sustainability,* 7**,** 212-214.

MURUGAN, R., BEGGI, F., PRABAKARAN, N., MAQSOOD, S. & JOERGENSEN, R. G. 2020. Changes in plant community and soil ecological indicators in response to Prosopis juliflora and *Acacia mearnsii* invasion and removal in two biodiversity hotspots in Southern India. *Soil Ecology Letters,* 2**,** 61-72.

MUVENGWI, J., MBIBA, M., JIMU, L., MUREVA, A. & DODZO, B. 2018. An assessment of the effectiveness of cut and ring barking as a method for control of invasive *Acacia mearnsii* in Nyanga National Park, Zimbabwe. *Forest Ecology and Management,* 427**,** 1-6.

NACHSHON, U. 2020. Soil degradation processes: It's time to take our head out of the sand. MDPI.

NAZ, M., DAI, Z., HUSSAIN, S., TARIQ, M., DANISH, S., KHAN, I. U., QI, S. & DU, D. 2022. The soil pH and heavy metals revealed their impact on soil microbial community. *Journal of Environmental Management,* 321**,** 115770.

NDOR, E., AMANA, S. & ASADU, C. 2015. Effect of biochar on soil properties and organic carbon sink in degraded soil of Southern Guinea Savanna Zone, Nigeria. *Int. J. Plant Soil Sci,* 4**,** 252-258.

NEGAWO, A. T., TESHOME, A., KUMAR, A., HANSON, J. & JONES, C. S. 2017. Opportunities for Napier grass (Pennisetum purpureum) improvement using molecular genetics. *Agronomy,* 7**,** 28.

NEIVA, D. M., GODINHO, M. C., SIMÕES, R. M. & GOMINHO, J. 2024. Encouraging Invasive Acacia Control Strategies by Repurposing Their Wood Biomass Waste for Pulp and Paper Production. *Forests,* 15**,** 822.

NELL, C., SCHENCK, C., JOUBERT, J., CHITAKA, T. & DE WIT, M. 2024. Disposable diaper usage, disposal practices and quantity estimation in rural areas. *Environmental Challenges,* 16**,** 101001.

NIU, Y. F., CHAI, R. S., JIN, G. L., WANG, H., TANG, C. X. & ZHANG, Y. S. 2013. Responses of root architecture development to low phosphorus availability: a review. *Annals of botany,* 112**,** 391-408.

NKONYA, E., JOHNSON, T., KWON, H. Y. & KATO, E. 2016. Economics of Land Degradation in Sub-Saharan Africa. In:. , . *Economics of Land Degradation and Improvement – A Global Assessment for Sustainable Development.* Cham: Springer.

NKONYA, E., PENDER, J., KAIZZI, K. C., KATO, E., MUGARURA, S., SSALI, H. & MUWONGE, J. 2008. Linkages between land management, land degradation, and poverty in Sub-Saharan Africa: The case of Uganda. *In:* INST, I. F. P. R. (ed.).

NORI, H., SANI, S. A. & TUEN, A. A. 2009. Chemical and physical properties of Sarawak (East Malaysia) rice straws. *Livestock Research for Rural Development,* 21**,** 80-87.

NTEGE, I., KIGGUNDU, N., WANYAMA, J. & NAKAWUKA, P. 2023. Napier yield response under different irrigation strategies in a tropical setting. *Agricultural Water Management,* 287**,** 108403.

NTEKPE, M. E., MBONG, E. O., EDEM, E. N. & HUSSAIN, S. 2019. Disposable nappies: impact of disposal methods on public health and the environment. *Am J Med Public Health,* 1**,** 1009.

NUNES, M. R., KARLEN, D. L., VEUM, K. S., MOORMAN, T. B. & CAMBARDELLA, C. A. 2020. Biological soil health indicators respond to tillage intensity: A US meta-analysis. *Geoderma,* 369**,** 114335.

NYAMBATI, E. M., MUYEKHO, F. N., ONGINJO, E. & LUSWETI, C. M. 2010. Production, characterization and nutritional quality of Napier grass [Pennisetum purpureum (Schum.)] cultivars in Western Kenya. *African Journal of Plant Science,* 4**,** 496-502.

ODIO, M. & THAMAN, L. 2014. Diapering, diaper technology, and diaper area skin health. *Pediatric dermatology,* 31**,** 9-14.

OGAWA, S. & YAZAKI, Y. 2018. Tannins from *Acacia mearnsii* De Wild. Bark: Tannin determination and biological activities. *Molecules,* 23**,** 837.

OLIVEIRA, M. L. F., DAHER, R. F., GRAVINA, G. D. A., SILVA, V. D., VIANA, A. P., RODRIGUES, E. V., SHIMOYA, A., AMARAL JUNIOR, A. D., MENEZES, B. D. S. & ROCHA, A. D. S. 2014. Pre-breeding of elephant grass for energy purposes and biomass analysis in Campos dos Goytacazes-RJ, Brazil. *African Journal of Agricultural Research,* 9**,** 2743-2758.

ONJAI-UEA, N., PAENGKOUM, S., TAETHAISONG, N., THONGPEA, S., SINPRU, B., SURAKHUNTHOD, J., MEETHIP, W., PURBA, R. A. P. & PAENGKOUM, P. 2022. Effect of cultivar, plant spacing and harvesting age on yield, characteristics, chemical composition, and anthocyanin composition of purple Napier grass. *Animals,* 13**,** 10.

PAN, S., SU, M., MENG, L., KE, X., XU, J. & LI, Z. 2024. Roles of phosphate-solubilizing microorganisms in soil–plant system: From phosphorus deficiency to oversupply. *Beneficial Microbes for Sustainable Agriculture Under Stress Conditions.* Elsevier.

PARKER, S. 2021. *The Environmental Impact of Disposable Nappies* [Online]. Ohio: Nicki's Nappies. Available: https://nickisnappies.com/blogs/switch-to-sustainable/the-

environmental-impact-of-disposable-nappies#:~:text=Disposable%20nappies%20account%20for%20around,a%20disposable%20diaper%20to%20decompose. [Accessed].

PATIL, A. A., KULKARNI, A. A. & PATIL, B. B. 2014. Waste to energy by incineration. *Journal of Computing Technologies,* 3**,** 12-15.

PIMENTEL, P., PELLEGRINI, C., LANNA, D. P. D., BRANT, L., RIBEIRO, C., SILVA, T., BARBOSA, A., DA SILVA JÚNIOR, J., BEZERRA, L. & OLIVEIRA, R. 2021. Effects of *Acacia mearnsii* extract as a condensed-tannin source on animal performance, carcass yield and meat quality in goats. *Animal Feed Science and Technology,* 271**,** 114733.

planting. *AGRICULTURE AND BIOLOGY JOURNAL OF NORTH AMERICA,* 1**,** 923-929.

POCH, R. M., DOS ANJOS, L. H., ATTIA, R., BALKS, M., BENAVIDES-MENDOZA, A., BOLAÑOS-BENAVIDES, M. M., CALZOLARI, C., CHABALA, L. M., DE RUITER, P. C. & FRANCKE-CAMPAÑA, S. 2020. Soil: the great connector of our lives now and beyond COVID-19. *SOIL Discussions,* 2020**,** 1-9.

POUDEL, A., ADHIKARI, P., ADHIKARI, P., CHOI, S. H., YUN, J. Y., LEE, Y. H. & HONG, S. H. 2024. Predicting the Invasion Risk of the Highly Invasive *Acacia mearnsii* in Asia under Global Climate Change. *Plants,* 13**,** 2846.

PRĂVĂLIE, R., PATRICHE, C., BORRELLI, P., PANAGOS, P., ROȘCA, B., DUMITRAŞCU, M., NITA, I.-A., SĂVULESCU, I., BIRSAN, M.-V. & BANDOC, G. 2021. Arable lands under the pressure of multiple land degradation processes. A global perspective. *Environmental Research,* 194**,** 110697.

RAHMAN, R. A., MANIKANDAN, K., SHENBAGAVALLI, S. & PRABHAKARAN, J. 2022. Assessment of germination percentage and growth parameters of different varieties of Napiergrass (Pennisetum purpureum) on sodic soil of Thoothukudi district, Tamil Nadu, India. *Journal of Applied and Natural Science,* 14**,** 45-50.

RAMBAU, M. D., FUSHAI, F. & J.J, B. 2016. Productivity, chemical composition and ruminal degradability of irrigated Napier grass leaves harvested at three stages of maturity. *South African Journal of Animal Science,* 46.

RANKOANA, S. A. 2022. A DESCRIPTION OF SMALL-SCALE FARMERS'INDIGENOUS HOUSEHOLD LIVELIHOOD STRATEGIES IN DIKGALE COMMUNITY IN LIMPOPO PROVINCE, SOUTH AFRICA. *Eurasian Journal of Social Sciences,* 10**,** 197-203.

REINHARDT, J. 2016. *Types of Cloth Baby Nappies* [Online]. Thinking About Cloth Nappies. Available: https://www.thinking-about-cloth-nappies.com/cloth-baby-nappies.html [Accessed].

REMIGIOS, M. 2014. The Environmental Health Implications of the Use and Disposal of Disposable Child Nappies in Senga, Nehosho Suburb in Gweru City, Zimbabwe. *Global Journal of Biology, Agriculture & Health Sciences,* 3**,** 122-127.

RENGSIRIKUL, K., ISHII, Y., KANGVANSAICHOL, K., SRIPICHITT, P., PUNSUVON, V., VAITHANOMSAT, P., NAKAMANEE, G. & TUDSRI, S. 2013. Biomass yield, chemical composition and potential ethanol yields of 8 cultivars of napiergrass (Pennisetum purpureum Schumach.) harvested 3-monthly in central Thailand. 3.

RENOU, S., GIVAUDAN, J. G., POULAIN, S., DIRASSOUYAN, F. & MOULIN, P. J. J. O. H. M., 2008. LANDFILL LEACHATE TREATMENT: REVIEW AND OPPORTUNITY. 150(3), PP.468-493. 2008. Landfill leachate treatment: Review and opportunity. *Journal of hazardous materials,,* 150**,** 468-493.

RICHARDSON, D. M., BINGGELI, P. & BOTELLA, C. 2023. Australian Acacia Species in Africa. *Wattles: Australian Acacia Species Around the World***,** 181-200.

ROJAS-SANDOVAL, J. & PASIECZNIK, N. 2022. *Acacia mearnsii* (black wattle). *CABI Compendium*.

RUWANZA, S. 2017. Invasion of abandoned agricultural fields by *Acacia mearnsii* affect soil properties in Eastern Cape, South Africa. *Appl. Ecol. Environ. Res,* 15**,** 127-139.

SADASIVAM, B. Y. & REDDY, K. R. 2015. Engineering properties of waste wood-derived biochars and biochar-amended soils. *International Journal of Geotechnical Engineering,* 9**,** 521-535.

SAMEC, P., KUČERA, A. & TOMÁŠOVÁ, G. 2023. Chapter Soil Degradation Processes Linked to Long-Term Forest-Type Damage.

SÁNCHEZ-OROZCO, R., TIMOTEO-CRUZ, B., TORRES-BLANCAS, T. & UREÑA-NÚÑEZ, F. 2017. Valorization of superabsorbent polymers from used disposable nappies as soil moisture conditioner.

SANTOS, R. V., MENDES, M. A., ALEXANDRE, C., CARROTT, M. R., RODRIGUES, A. & FERREIRA, A. F. 2022. Assessment of biomass and biochar of maritime pine as a porous medium for water retention in soils. *Energies,* 15**,** 5882.

SARANGI, D., JENA, D., SANTRA, G. H. & CHOUDHURY, S. 2020. Effect of low grade rock phosphate, single super phosphate and their mixtures on soil exchangeable calcium, Δ Ca in a groundnut-maize cropping system on the acid Alfisols of Odisha state, India over two years. *IJCS,* 8**,** 559-564.

SEN, P., KANTAREDDY, S. N. R., BHATTACHARYYA, R., SARMA, S. E. & SIEGEL, J. E. 2019. Low-cost diaper wetness detection using hydrogel-based RFID tags. *IEEE Sensors Journal,* 20**,** 3293-3302.

SHAHIDIAN, S., SERRALHEIRO, R., SERRANO, J., MACHADO, R., TOUREIRO, C. & REBOCHO, J. 2010. Use of Diaper Polymers as Soil Conditioner. *Ghanaian Journal of Animal Science,* 10**,** 55-61.

SHANG, X. 2019. *Effect of wood-based biochar on soil quality, small fruit yield and quality in southern Quebec, Canada*, McGill University (Canada).

SHIDDIQ, M. A., PRAMUDIA, D., NEFILINDA, N., SYUKRIANI, L. & JAMSARI, J. Metagenomic Profile of Endophytic Bacteria in *Acacia mearnsii*. IOP Conference Series: Earth and Environmental Science, 2023. IOP Publishing, 012030.

SIBIYA, S., CLIFFORD-HOLMES, J. K. & GAMBIZA, J. 2023. Drivers of Degradation of Croplands and Abandoned Lands: A Case Study of Macubeni Communal Land in the Eastern Cape, South Africa. *Land,* 12**,** 606.

SILVA, T., MAGNANI, E., DE ANDRADE, J., AMÂNCIO, B., MEURER, G., REOLON, H., BENEDETI, P., PAULA, E. & BRANCO, R. 2024. Evaluation of increasing levels of condensed tannin extracted from *Acacia mearnsii* on performance, carcass traits, meat quality, methane emission, and health of finishing Nellore bulls. *Animal Feed Science and Technology,* 315**,** 116046.

ŠIMANSKÝ, V., HORÁK, J., IGAZ, D., BALASHOV, E. & JONCZAK, J. 2018. Biochar and biochar with N fertilizer as a potential tool for improving soil sorption of nutrients. *Journal of Soils and Sediments,* 18**,** 1432-1440.

SINGH, A. K., ZHU, X., CHEN, C., WU, J., YANG, B., ZAKARI, S., JIANG, X. J., SINGH, N. & LIU, W. 2022. The role of glomalin in mitigation of multiple soil degradation problems. *Critical Reviews in Environmental Science and Technology,* 52**,** 1604-1638.

SINGH, J., KUMAR, A. & DHALIWAL, A. 2023. Superabsorbent Polymers Application in Agriculture Sector. *Properties and Applications of Superabsorbent Polymers: Smart Applications with Smart Polymers***,** 83-117.

SIREGAR, M. J. 2022. Recent Technology for Recycling of Used Nappies Waste. *International Journal of Innovation in Engineering,* 2**,** 13-25.

SOARES, G. M., SILVA, L. D., HIGA, A. R., SIMON, A. A. & JOSÉ, J. D. S. 2018. Growth of *Acacia mearnsii* De Wild and Eucalyptus globulus Labill in monoculture and mixed-plantations with simple lines and double lines of planting.

SOP 2005. Elemental analysis of solution samples with inductively coupled plasma optical emission spectrometry. *Soil and Plant Analysis Laboratory. University of Wisconsin-Madison***,** 2-4.

SPRYNCHUK, N., VORONETSKA, I., YUDOVA, O., KORNIYCHUK, O. & ZADOROZHNA, I. 2023. Priority areas for the development of field fodder production in view of the climate crisis. *Ekonomika APK,,* 30**,** 34-44.

SPURRIER, J. & BUCK, A. 2015. *Green Nappies vs. Traditional: What's the Best Choice?* [Online]. Available: https://www.babygearlab.com/expert-advice/green-nappies-vs-traditional-whats-the-best-choice [Accessed].

STRYDOM, M., VELDTMAN, R., NGWENYA, M. Z. & ESLER, K. J. 2017. Invasive Australian Acacia seed banks: Size and relationship with stem diameter in the presence of gall-forming biological control agents. *PloS one,* 12**,** e0181763.

SUPARE, K. & MAHANWAR, P. A. 2022. Starch-derived superabsorbent polymers in agriculture applications: an overview. *Polymer Bulletin,* 79**,** 5795-5824.

TAHERABADI, L. & KAFILZADEH, F. 2023. Nutritive value of Napier grass at different growth stages. *Animal Production,* 25**,** 83-91.

TAMTA, S., KUMAR, A. & KUSHWAHA, D. P. 2023. Potential of roots and shoots of Napier grass for arresting soil erosion and runoff of mollisols soils of Himalayas. *International Soil and Water Conservation Research,* 11**,** 538-548.

TANG, B., ROCCI, K. S., LEHMANN, A. & RILLIG, M. C. 2023. Nitrogen increases soil organic carbon accrual and alters its functionality. *Global Change Biology,* 29**,** 1971-1983.

TAVIRIMIRWA, B., MANZUNGU, E. & NCUBE, S. 2012. The evaluation of dry season nutritive value of dominant and improved grasses in fallows in Chivi district, Zimbabwe. *Online Journal of Animal and Feed Research,* 2**,** 470-474.

TENG, C., ZHOU, K., PENG, C. & CHEN, W. 2021. Characterization and treatment of landfill leachate: A review. *Water research,* 203**,** 117525.

TESSEMA, Z. & BAARS, R. M. T. 2004. Chemical composition, in vitro dry matter digestibility and ruminal degradation of Napier grass (Pennisetum purpureum (L.) Schumach.) mixed with different levels of Sesbania sesban (L.) Merr. *Animal feed science and technology,* 117**,** 29-41.

THAMAN, L. A. & EICHENFIELD, L. F. 2014. Diapering habits: a global perspective. *Pediatric dermatology,* 31**,** 15-18.

THOMAS-POSSEE, M. L., SHAW, P. J., BAIN, R. E., HILL, A. G., OKOTTO-OKOTTO, J., OKOTTO, L. G., DZODZOMENYO, M. & WRIGHT, J. A. 2024. Disposable diaper consumption in sub-Saharan Africa: Estimating the risks of associated unsafe waste. *PLOS Sustainability and Transformation,* 3**,** e0000106.

TRIPATHI, A. & MELO, J. S. 2020. An overview on super absorbent polymer and its application in agriculture. *INDIAN ASSOCIATION OF NUCLEAR CHEMISTS AND ALLIED SCIENTISTS***,** 38.

TULLY, K., SULLIVAN, C., WEIL, R. & SANCHEZ, P. 2015. The state of soil degradation in Sub-Saharan Africa: Baselines, trajectories, and solutions. *Sustainability,* 7**,** 6523-6552.

TURANO, B., TIWARI, U. P. & JHA, R. 2016. Growth and nutritional evaluation of napier grass hybrids as forage for ruminants. *Tropical Grasslands-Forrajes Tropicales,* 4**,** 168-178.

USMAN, K., KHAN, S., GHULAM, S., KHAN, M. U., KHAN, N., KHAN, M. A. & KHALIL, S. K. 2012. Sewage sludge: an important biological resource for sustainable agriculture and its environmental implications. *American Journal of Plant Sciences,* 3**,** 1708-1721.

UTAMI, K., HANUDIN, E. & NURUDIN, M. 2020. The kinetics curve of nitrogen mineralization from perennial leaves litter decomposed by earthworm (Phretima californica). *SAINS TANAH-Journal of Soil Science and Agroclimatology,* 17**,** 152-160.

UTUK, I. O. & DANIEL, E. E. 2015. Land Degradation: A Threat to Food Security: A Global Assessment. *Journal of Environment and Earth Science,* 5.

VAN SOEST, P. J., B, R. J. & A, L. B. 1991. Methods for dietary fiber, neutral detergent fiber, and non-starch polysaccharides in relation to animal nutrition. *Journal of Dairy Science,* 74**,** 3583-3597.

VAVERKOVÁ, M. D. 2019. Landfill Impacts on the Environment—Review. *Geosciences,* 9**,** 431.

VENTER, M., HASSEN, A., POPHIWA, P. & WEBB, E. C. 2024. Effects of dietary supplementation with *Acacia mearnsii* tannin extract on carcass characteristics and meat quality of lambs. *CABI Agriculture and Bioscience,* 5**,** 69.

WANG, C., LUO, D., ZHANG, X., HUANG, R., CAO, Y., LIU, G., ZHANG, Y. & WANG, H. 2022. Biochar-based slow-release of fertilizers for sustainable agriculture: A mini review. *Environmental Science and Ecotechnology,* 10**,** 100167.

WANG, J., XIONG, Z. & KUZYAKOV, Y. 2016. Biochar stability in soil: meta-analysis of decomposition and priming effects. *Gcb Bioenergy,* 8**,** 512-523.

WANG, R., WANG, Y., ZHANG, Z., PAN, H., LAN, L., HUANG, R., DENG, X. & PENG, Y. 2023. Effects of Exponential N Application on Soil Exchangeable Base Cations and the Growth and Nutrient Contents of Clonal Chinese Fir Seedlings. *Plants,* 12**,** 851.

WARAMIT, N. & CHAUGOOL, J. 2014. Napier grass: a novel energy crop development and the current status in Thailand. *Journal of ISSAAS,* 20**,** 139-150.

WHITE, H. L., MWAPASA, T., MPHASA, M., KALONDE, P. K., FEASEY, N., OLIVER, D. M., ORMSBY, M. J., MORSE, T., CHIDZIWISANO, K. & QUILLIAM, R. S. 2023. Open defaecation by proxy: Tackling the increase of disposable nappies in waste piles in informal settlements. *International Journal of Hygiene and Environmental Health,* 250**,** 114171.

WILSON, J. R., GAIRIFO, C., GIBSON, M. R., ARIANOUTSOU, M., BAKAR, B. B., BARET, S., CELESTI-GRAPOW, L., DITOMASO, J. M., DUFOUR-DROR, J. M. & KUEFFER, C. 2011. Risk assessment, eradication, and biological control: global efforts to limit Australian acacia invasions. *Diversity and distributions,* 17**,** 1030-1046.

WRESTA, A., NILAWATI, D., PUTRA, H. E., INDRIATI, L., SINTAWARDANI, N., FITRIA, N., HAMIDAH, U., PURWANTA, W., PERMANA, D., SETIAWAN, A. A. R. & PUTRI, G. A. 2024. Reclaiming resources from disposable nappies: Closing the loop with hydrothermal carbonization and water reuse. *Energy Conversion and Management,,* 315**,** 118813.

XIONG, D., CHEN, J. & YU, T. 2015. SPAD-based leaf nitrogen estimation is impacted by environmental factors and crop leaf characteristics. *Scientific reports,* 5**,** 13389

XO, S. 2015. *Help! Which Cloth Diaper is Right for Me?* [Online]. modhomemaker. Available: https://www.modhomemaker.com/2015/01/help-which-cloth-diaper-is-right-for-me.html [Accessed].

XU, H., FANG, S., TAN, L., LI, Y., WANG, Y., MA, Y., LIU, X., ZAAROUR, B. & LIU, W. 2024. A comprehensive evaluation of the most-sold baby nappies on the market. *Textile Research Journal,* 0**,** 00405175231215097.

XU, H., FANG, S., TAN, L., LI, Y., WANG, Y., MA, Y., LIU, X., ZAAROUR, B. & LIU, W. 2024. A comprehensive evaluation of the most-sold baby diapers on the market. *Textile Research Journal,* 0**,** 00405175231215097.

YADAV, K. D., TARE, V. & AHAMMED, M. M. 2010. Vermicomposting of source-separated human faeces for nutrient recycling. *Waste Management,* 30**,** 50-56.

YAN, B., SUN, Y. Y. & WEI, Y. 2020. Potassium–calcium antagonistic interaction under tomato magnesium deficiency and magnesium fertiliser regulation in solar greenhouse. *Quality Assurance and Safety of Crops and Foods,* 12**,** 76-86.

YANG, J., XU, X., LIU, M., XU, C., LUO, W., SONG, T., DU, H. & KIELY, G. 2016. Effects of Napier grass management on soil hydrologic functions in a karst landscape, southwestern China. *Soil and Tillage Research,* 157**,** 83-92.

YAWSON, D. O., AMOAH, K. K., ASARE, P. A., TECHIE-MENSON, J., AFUTU, E., ATIAH, K., SANLERI, A. K., ASARE-LARBI, S. & ADU, M. O. 2020. A Meta-Analysis of Modifications of Root System Traits of Crop Plants to Potassium (K)

Deprivation. *In:* YILDRIM, E., TURAN, M. & EKINCI, M. (eds.) *Plant Roots.* IntechOpen.

ZAILAN, M. Z., YAAKUD, H. & JUSOH, S. 2018. Yield and nutritive quality of Napier (Pennisetum purpureum) cultivars as fresh and ensiled fodder. *JAPS: Journal of Animal & Plant Sciences,* 28.

ZAITSEV, Y., SOBKO, V., KOZHEVNIKOVA, V., LOBANOVA, O. & KYRYLCHUK, A. 2022. Classification of processes that cause land degradation. *Agroecological journal***,** 150-159.

ZEKRY, M., NASSAR, I., SALIM, H. & ABDALLAH, A. 2020. The Potential of super absorbent polymers from diaper wastes to enhance water retention properties of the soil. *Soil & Environment,* 39.

ZEWDU, T., BAARS, R. & YAMI, A. 2002. Effect of plant height at cutting, source and level of fertiliser on yield and nutritional quality of Napier grass (Pennisetum purpureum (L.) Schumach.). *African journal of range and Forage Science,* 19**,** 123-128.

ZHANG, F., NIU, J., ZHANG, W., CHEN, X., LI, C., YUAN, L. & XIE, J. 2010. Potassium nutrition of crops under varied regimes of nitrogen supply. *Plant and Soil,* 335**,** 21-34.

ZHANG, R., YANG, P., LIU, S., WANG, C. & LIU, J. 2022. Evaluation of the methods for estimating leaf chlorophyll content with SPAD chlorophyll meters. *Remote Sensing,* 14**,** 5144.

ZIA-UR-REHMAN, M., MURTAZA, G., QAYYUM, M. F., SAIFULLAH, RIZWAN, M., ALI, S., AKMAL, F. & KHALID, H. 2016. Degraded soils: origin, types and management. *Soil science: Agricultural and environmental prospectives***,** 23-65.

ZURAIDA, S. 2023. *Study on recycling of disposable diaper as ecofriendly-concrete material for the application on building.* Doctorate Manuscript, The University of Kitakyushu.