**BINDURA UNIVERSITY OF SCIENCE EDUCATION**

**FACULTY OF SCIENCE AND ENGINEERING**

**DEPARTMENT OF CHEMISTRY**

# ENVIRONMENTAL ASSESSMENT OF SOIL AND WATER QUALITY AROUND A NITROGEN BASED FERTILIZER BLENDING FACILITY IN ZIMBABWE: CASE STUDY OF SUPERFERT (PVT) (LTD)

**By**

**TANATSWA T CHAYIBVA**

**REG NO: B221110B**

Supervisor: Dr W.MUNZEIWA

Level: 4.2

A dissertation submitted in partial fulfilment of the requirements for the award of the BACHELOR OF SCIENCE (HONOURS) DEGREE IN CHEMICAL TECHNOLOGY

**2026**

# APPROVAL FORM

The undersigned attest to their supervision and recommendation to Bindura University of Science Education for the approval of a research dissertation entitled:

**ENVIRONMENTAL ASSESSMENT OF SOIL AND WATER QUALITY AROUND A NITROGEN BASED FERTILIZER BLENDING FACILITY IN ZIMBABWE: CASE STUDY OF SUPERFERT (PVT) (LTD)**

Submitted by TANATSWA T CHAYIBVA

In partial fulfilment of the BACHELOR OF SCIENCE (HONOURS) DEGREE IN CHEMICAL TECHNOLOGY, with the approval of the listed supervisors:

Student's Signature …… …… Date: ……

Principal Supervisor's Signature …… …… Date:24/06/25 ……

Chairperson's Signature …… …… Date: ……22/08/2026……

## DECLARATION

I, Tanatswa Chayibva, hereby declare that this dissertation, titled "Environmental Assessment of Soil and Water Quality around a Nitrogen Based Fertilizer Blending Facility in Zimbabwe" is my original work. I have not submitted it, in whole or in part, for any other degree or examination at this or any other university. I further confirm that all sources, quotations, and ideas from the work of others have been clearly acknowledged and referenced in accordance with standard academic guidelines.

Signature of Student: …  ……

## DEDICATION

To my family,

This work is wholeheartedly dedicated to my family — my parents and siblings — whose unwavering love, sacrifices, and constant encouragement have been the foundation of every achievement in my life. Your belief in me never wavered, even during the most challenging moments of this research journey. You celebrated every small milestone and lifted my spirits when the weight of long laboratory hours and the demands of final year felt overwhelming.

To my friends and colleagues who walked this road alongside me — thank you for the late-night study sessions, the shared laughter, and the mutual support. This accomplishment belongs to all of you. May this work serve as a testament to what dedication, perseverance, and the support of loved ones can achieve.

## ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to Almighty God for granting me the strength, wisdom, good health, and perseverance throughout the course of this study.

My heartfelt appreciation goes to my supervisor, Dr Munzeiwa, whose invaluable guidance, constructive criticism, encouragement, and professional expertise greatly contributed to the successful completion of this research project. Your commitment to academic excellence and your patience in guiding me through the complexities of environmental impact research have been truly inspiring.

I am equally grateful to the Department of Chemistry at Bindura University of Science Education (BUSE) for providing the academic environment, technical support, and laboratory facilities necessary for conducting this study. Special thanks are extended to all lecturers and technical staff within the Faculty of Science and Engineering for their guidance and assistance during my undergraduate studies.

I would like to acknowledge my family for their unwavering support, patience, prayers, and motivation throughout my academic journey. Their sacrifices and belief in my abilities provided the foundation upon which this achievement rests.

I am equally thankful to my friends and classmates for their encouragement, valuable discussions, and support during the execution of this research project.

Finally, I extend my sincere appreciation to everyone who contributed directly or indirectly to the successful completion of this study. Your support is greatly appreciated.

May God bless you all.

## Table of Contents

**DECLARATION** ..... **3**

**DEDICATION** ..... **4**

**ACKNOWLEDGEMENTS** ..... **5**

**Table of Contents** ..... **6**

**Chapter One: Introduction** ..... **12**

1.1 Background of the Study ..... 12

1.2 Problem Statement ..... 13

1.3 Objectives ..... 14

1.4 Research Questions ..... 14

1.5 Significance of the Study ..... 15

1.6 Justification of the Study ..... 16

1.7 Hypotheses ..... 16

1.8 Limitations of the Study ..... 17

1.9 Chapter Summary ..... 17

**Chapter Two: Literature Review** ..... **18**

2.1 Introduction ..... 18

2.2 Theoretical Framework ..... 18

2.3 Nitrogen Fertilizer Use and Environmental Concerns: Global Perspective ..... 18

2.4 Behaviour of Nitrogen Compounds in Soil ..... 19

2.5 Nitrate Mobility and Water Quality ..... 20

2.6 Soil and Water Quality Indicators in Nitrogen Pollution Studies ..... 22

2.7 Environmental Studies of Fertilizer Industrial Facilities versus Field Application ..... 23

2.8 Distance Based Sampling and Use of Control Sites ..... 24

2.9 Identified Knowledge Gaps ..... 24
2.10 Chapter Summary ..... 25
**Chapter Three: Research Methodology ..... 26**
3.1 Introduction ..... 26
3.2 Research Philosophy and Approach ..... 26
3.3 Research Design ..... 26
3.4 Research Hypotheses ..... 27
3.5 Sampling Strategy ..... 27
3.5.1 Soil Sampling Locations ..... 27
3.5.2 Water Sampling Locations ..... 28
3.6 Sample Collection, Handling, and Preservation ..... 29
3.6.1 Soil Sample Collection ..... 29
3.6.2 Water Sample Collection ..... 29
3.7 Laboratory Analytical Procedures for Water Quality ..... 30
3.7.1 Determination of Nitrate ($NO_3^-$) in Borehole Water ..... 30
3.7.1.1 Preparation of Nitrate Standards ..... 30
3.7.1.2 Instrument Standardization and Sample Analysis ..... 30
3.7.2 Determination of Ammonium ($NH_4^+$) in Borehole Water ..... 31
3.7.2.1 Reagent Preparation ..... 32
3.7.2.2 Distillation and Titration Procedure ..... 32
3.7.3 Determination of Water pH and Electrical Conductivity ..... 33
3.7.3.1 Water pH ..... 33
3.7.3.2 Water Electrical Conductivity ..... 33
3.8 Laboratory Analytical Procedures for Soil Quality ..... 34
3.8.1 Determination of Total Nitrogen in Soils by the Modified Kjeldahl Method ..... 34

3.8.1.1 Reagent Preparation ..... 34
3.8.1.2 Extraction and Distillation Procedure ..... 35
3.8.2 Determination of Soil pH ..... 36
3.8.2.1 Sample Preparation ..... 36
3.8.3 Determination of Soil Electrical Conductivity ..... 36
3.8.3.1 Sample Preparation and Measurement ..... 36
3.9 Quality Assurance and Quality Control ..... 37
3.10 Data Analysis ..... 38
3.11 Ethical Considerations ..... 39
3.12 Chapter Summary ..... 39
**Chapter Four: Results and Discussion ..... 40**
4.1 Introduction ..... 40
4.2 Borehole Water Quality Results ..... 40
4.2.1 Nitrate ($NO_3^-$) Concentration in Borehole Water ..... 40
4.2.2 Ammonium Nitrogen ($NH_4^+$-N) in Borehole Water ..... 43
4.2.3 Water pH and Electrical Conductivity ..... 44
4.3 Soil Quality Results ..... 46
4.3.1 Total Nitrogen in Soil ..... 46
4.3.2 Soil pH ..... 49
4.3.3 Soil Electrical Conductivity ..... 51
4.4 General Discussion ..... 52
4.5 Chapter Summary ..... 53
**Chapter Five: Conclusions and Recommendations ..... 54**
5.1 Introduction ..... 54
5.2 Summary of Key Findings ..... 54

5.3 Conclusions in Relation to Research Objectives ..... 55
5.3.1 Objective One: Soil Quality Characteristics Near the Superfert Facility ..... 55
5.3.2 Objective Two: Water Quality in Nearby Groundwater Sources ..... 55
5.3.3 Objective Three: Comparison Between Impact and Control Sites ..... 55
5.4 Contextualisation within the Broader Literature ..... 56
5.5 Implications for Environmental Management ..... 56
5.6 Implications for Policy and Regulation ..... 57
5.7 Limitations of the Study and Directions for Future Research ..... 58
5.8 Final Conclusions ..... 59
5.9 Chapter Summary ..... 60
**References ..... 61**

**List of Abbreviations**

- APHA — American Public Health Association.
- ATC — Automatic Temperature Compensation.
- CaCl — Calcium Chloride.
- EC — Electrical Conductivity.
- H2SO4 — Sulfuric Acid.
- KCl — Potassium Chloride.
- NH3 — Ammonia.
- NH4+ — Ammonium ion.
- NO2- — Nitrite ion.
- NO3- — Nitrate ion.
- pH — Potential of Hydrogen.
- QAQC — Quality Assurance and Quality Control.
- SPSS — Statistical Package for the Social Sciences.
- TDS — Total Dissolved Solids.
- UV — Ultraviolet.
- WHO — World Health Organization.
- ZEMA — Zimbabwe Environment Management Agency.

**Abstract**

This study assessed the possible environmental impact of Superfert Pvt Ltd, a fertilizer blending facility in Zimbabwe, on surrounding soil and borehole water quality. Using a quantitative, comparative case study design, samples were collected from impact locations near the facility and from control sites outside the expected zone of influence. Laboratory analyses focused on nitrate, ammonium, total soil nitrogen, soil pH, and electrical conductivity, applying standard methods and quality assurance procedures. The results showed consistently higher nitrate, ammonium, total nitrogen, and electrical conductivity at impact sites, together with lower pH values, suggesting a localized enrichment of nitrogen compounds and soluble salts associated with facility operations. Although the measured concentrations generally remained within accepted drinking-water guideline limits, the spatial pattern indicates a measurable environmental gradient linked to proximity to the blending plant. The study concludes that fertilizer handling activities may contribute to altered soil and water chemistry in the immediate surroundings and recommends continued monitoring, wider spatial sampling, and seasonal follow-up studies to better define the extent and persistence of the observed effects.

Environmental Assessment of Soil and Water Quality Around a Nitrogen Based Fertilizer Blending Facility in Zimbabwe: Case Study of Superfert Pvt Ltd.

# Chapter One: Introduction

## 1.1 Background of the Study

Nitrogen based fertilizers play a central role in improving agricultural productivity by supplying essential nutrients required for plant growth and increasing crop yields. In Zimbabwe, fertilizer use remains an important input for both commercial and smallholder farming systems where soils are often nutrient depleted and require external nutrient supplementation to sustain production (Wuta et al., 2016). The increased reliance on nitrogen fertilizers reflects broader global agricultural trends in which synthetic nitrogen inputs contribute significantly to food security through improved productivity and soil fertility management (Anas et al., 2020). However, while nitrogen fertilizers provide agronomic benefits, their environmental behavior raises concerns due to the high mobility of nitrogen compounds such as nitrate and ammonium in soil and water systems.

Nitrogen compounds are highly soluble and prone to leaching, which increases the risk of groundwater contamination and nutrient enrichment of surface water bodies. Studies conducted in Zimbabwean agricultural environments indicate that groundwater contamination by nitrate becomes more likely in areas with intensive fertilizer application, especially during periods of agricultural activity when nitrogen inputs are highest (Wuta et al., 2016). Local water quality investigations in Zimbabwe have also demonstrated variability in groundwater chemistry influenced by anthropogenic activities, highlighting the importance of monitoring potential pollution sources near industrial or agricultural operations (Makaya, 2023). These findings suggest that nitrogen related environmental risks are context dependent and require site specific evaluation rather than reliance on generalized assumptions.

Globally, nitrogen fertilizer use has been strongly associated with environmental impacts including nitrate pollution, greenhouse gas emissions, and alterations in soil chemistry. Research indicates that less than half of applied fertilizer nitrogen is directly taken up by crops, with significant portions remaining in the soil or lost through leaching and gaseous emissions pathways (Bijay Singh & Craswell, 2021). Such losses contribute to environmental concerns such as eutrophication,

groundwater nitrate accumulation, and increased emissions of nitrous oxide, a potent greenhouse gas linked to agricultural intensification (Martínez-Dalmau et al., 2021). The environmental fate of nitrogen therefore depends on multiple factors including handling practices, storage conditions, climate, and proximity of industrial or agricultural sources to sensitive ecosystems.

Although much research has focused on agricultural field application of fertilizers, fewer studies examine the environmental influence of fertilizer blending and production facilities themselves. Industrial handling, storage, and distribution of nitrogen-based fertilizers may contribute to localized environmental changes through dust emissions, accidental nutrient release, or runoff pathways affecting nearby soils and water systems. Case studies assessing environmental quality indicators near potential pollution sources have shown that distance-based sampling and comparison with control sites provide effective approaches for identifying anthropogenic impacts (Odiyo et al., 2018). Such approaches are particularly relevant in developing country contexts where environmental monitoring data are limited.

In Zimbabwe, research specifically addressing the environmental footprint of fertilizer blending plants remains scarce, creating a knowledge gap regarding whether such facilities contribute to measurable environmental changes in surrounding areas. Given the potential for nitrogen mobility and the importance of protecting soil and water resources, localized environmental assessment becomes essential for evaluating sustainability of industrial activities. The Superfert Pvt Ltd fertilizer blending facility provides an opportunity to conduct a site-specific case study by assessing soil and water quality indicators around the plant and comparing results with control locations beyond potential influence zones. Generating empirical evidence from such assessments contributes to improved understanding of environmental risk pathways and supports development of evidence based environmental management strategies within the Zimbabwean industrial context.

### 1.2 Problem Statement

Nitrogen based fertilizer blending plants play an important role in supporting agricultural productivity in Zimbabwe through the supply of essential nutrients. However, industrial handling and storage of nitrogen rich fertilizers may influence surrounding environmental conditions through nutrient deposition, dust emissions, and potential leakage or runoff into nearby soils and

water bodies. Superfert Pvt Ltd operates a fertilizer blending facility whose long-term environmental effects on the surrounding area have not been systematically evaluated.

Nitrogen compounds such as nitrates and ammoniums are highly mobile in the environment and, when released beyond intended boundaries, may contribute to soil chemical changes, groundwater contamination, and nutrient enrichment of nearby ecosystems. Despite these potential risks, limited localized studies exist assessing whether fertilizer blending facilities in Zimbabwe produce measurable environmental impacts on surrounding soil and water quality. Without site specific environmental assessment, it remains unclear whether observed environmental conditions around the plant reflect natural background variation or influence from fertilizer related activities.

A focused environmental case study is therefore required to evaluate environmental quality indicators in areas surrounding the Superfert facility, with emphasis on nitrogen related parameters. Such assessment provides evidence needed to determine whether proximity to the fertilizer plant associates with measurable environmental changes and contributes to understanding sustainable industrial practices within the Zimbabwean context.

### 1.3 Objectives

1. To determine soil quality characteristics in areas surrounding the Superfert fertilizer blending plant by measuring nitrogen related parameters such as nitrate concentration, ammonium levels, soil pH, and electrical conductivity at selected sampling distances.
2. To evaluate water quality in nearby surface and or groundwater sources by analyzing nitrate concentration and selected physicochemical parameters associated with nitrogen contamination.
3. To compare environmental quality indicators between locations which are close to the plant and control sites located outside the potential zone of influence in order to assess whether proximity to the fertilizer facility associates with measurable environmental changes.

### 1.4 Research Questions

1. What are the soil quality characteristics, including nitrate concentration, ammonium levels, soil pH, and electrical conductivity, in areas surrounding the Superfert fertilizer blending plant?

2. What are the nitrate concentrations and related physicochemical properties of nearby surface and or groundwater sources located within the vicinity of the Superfert facility?
3. Are there significant differences in soil and water quality indicators between locations close to the fertilizer plant and control sites situated outside the potential zone of influence?
4. Does proximity to the Superfert fertilizer blending facility associate with measurable environmental changes in soil and water quality based on nitrogen related parameters?

### 1.5 Significance of the Study

This study provides site specific environmental evidence regarding the potential impacts of a nitrogen-based fertilizer blending facility on surrounding soil and water quality. By generating empirical data on nitrogen related environmental indicators such as nitrate concentration, ammonium levels, soil pH, and electrical conductivity, the research contributes to improved understanding of how industrial fertilizer activities associate with environmental conditions within the Zimbabwean context. The findings add localized scientific data to a research area where plant level environmental assessments remain limited.

The study supports environmental monitoring and management by identifying whether measurable environmental changes occur in areas surrounding the Superfert facility. Such information assists regulatory authorities, environmental agencies, and industry stakeholders in evaluating compliance with environmental protection standards and in strengthening monitoring frameworks where necessary. Evidence based assessment reduces reliance on assumptions and enables more informed decision making regarding industrial environmental management.

From an academic perspective, the research contributes to the existing body of knowledge by addressing a gap in localized studies focusing on fertilizer blending plants rather than agricultural application alone. Many environmental studies examine fertilizer use at field level, while fewer investigate environmental quality around fertilizer production or blending sites. This case study therefore expands understanding of potential environmental impact pathways linked to industrial fertilizer handling and storage.

The study also has practical value for industry by providing data which assist in evaluating current environmental management practices. Identifying areas where environmental indicators remain within acceptable limits or where deviations occur provides guidance for improving mitigation

strategies, operational monitoring, and environmental risk reduction. Such findings support sustainable industrial practices aligned with national environmental protection goals.

### 1.6 Justification of the Study

Nitrogen compounds such as nitrate and ammonium are mobile in soil and water systems and can move beyond intended industrial boundaries through runoff, leaching, or atmospheric deposition. Given the presence of a fertilizer blending facility handling nitrogen rich materials, it is scientifically necessary to determine whether surrounding environmental media show measurable changes associated with plant proximity. Without site specific assessment, environmental conditions may be attributed to natural variation without empirical verification.

This study is justified by the limited availability of localized research examining environmental conditions around fertilizer blending facilities in Zimbabwe. Most existing work focuses on agricultural field application rather than industrial storage and handling sites. A focused case study provides baseline environmental data that can support regulatory monitoring, environmental management planning, and future comparative studies.

The research is also justified from a sustainability perspective. Soil and water resources are critical for agriculture, public health, and ecosystem stability. Generating evidence on whether industrial fertilizer activities associate with changes in nitrogen related environmental indicators supports informed environmental governance and responsible industrial practice.

### 1.7 Hypotheses

Null Hypothesis: There is no significant difference in soil and water quality indicators, including nitrate concentration, ammonium levels, soil pH, and electrical conductivity, between locations near the Superfert fertilizer blending plant and control sites outside the zone of influence.

Alternative Hypothesis: There is a significant difference in soil and water quality indicators, including nitrate concentration, ammonium levels, soil pH, and electrical conductivity, between locations near the Superfert fertilizer blending plant and control sites outside the zone of influence.

## 1.8 Limitations of the Study

The study is geographically limited to areas surrounding the Superfert facility and selected control sites. Findings cannot be generalized to all fertilizer blending plants in Zimbabwe without further comparative studies.

Temporal limitations may affect results because sampling represents environmental conditions at specific points in time. Seasonal variations in rainfall and temperature can influence nitrate mobility, soil chemistry, and water quality, which may not be fully captured within a single sampling period.

Attribution of environmental changes solely to the fertilizer plant may be constrained by the presence of other potential pollution sources such as nearby agricultural activities, residential areas, or natural background variability. While distance-based comparison reduces this limitation, it does not eliminate all confounding factors.

Resource and equipment constraints at undergraduate level may limit the range of environmental parameters analyzed. The study focuses primarily on selected nitrogen related indicators and may not include comprehensive atmospheric emission measurements or long-term monitoring data.

## 1.9 Chapter Summary

This chapter introduced the environmental context of nitrogen-based fertilizer blending and its potential effects on surrounding soil and water quality. The background highlighted the importance of nitrogen fertilizers in Zimbabwean agriculture and identified environmental concerns linked to nitrate mobility and contamination pathways. The problem statement emphasized the lack of localized studies assessing environmental impacts around fertilizer blending facilities, establishing the need for a case study of the Superfert plant. Research objectives and questions were developed to guide assessment of soil and water quality indicators and comparison between sites near the facility and control locations. The significance, justification, hypotheses, and study limitations were outlined, providing a clear conceptual and methodological foundation for evaluating potential environmental changes associated with plant proximity.

# Chapter Two: Literature Review

## 2.1 Introduction

This chapter reviews the scientific literature relevant to the environmental assessment of soil and water quality around nitrogen based fertilizer facilities. The review begins with the global context of nitrogen fertilizer use and its environmental implications, then narrows to the behaviour of nitrogen compounds in soil and water systems, the indicator parameters used to detect nitrogen related contamination, and the comparatively limited body of work that has examined fertilizer handling and blending sites as opposed to fertilizer application on farmland. Throughout the chapter, methodological and interpretive limitations of cited studies are discussed in order to identify the gaps that the present study addresses.

## 2.2 Theoretical Framework

The conceptual basis of this study is drawn from the source–pathway–receptor model commonly used in environmental risk assessment. In this framework, a fertilizer blending facility is treated as a potential point source of nitrogen rich material, the surrounding soil and water bodies act as receptors, and the pathways linking them include surface runoff, leaching, dust deposition, and ammonia volatilization followed by atmospheric redeposition. The framework is supported by an understanding of the nitrogen cycle, in which inorganic forms such as ammonium and nitrate undergo continuous transformation through nitrification, denitrification, plant uptake, and mineralization, with each transformation altering the form, mobility, and environmental fate of the nutrient (Anas et al., 2020). Distance based sampling, as adopted in this study, operationalises the framework by assuming that if a measurable source–pathway–receptor link exists, the magnitude of the impact should attenuate with distance from the source provided no other significant nitrogen inputs intervene.

## 2.3 Nitrogen Fertilizer Use and Environmental Concerns: Global Perspective

Nitrogen is the macronutrient most often limiting in agricultural systems, and synthetic nitrogen fertilizers have been central to the productivity gains of the last several decades (Anas et al., 2020). However, the environmental cost of this dependence has been increasingly documented. Bijay-Singh and Craswell (2021) provide a comprehensive global review showing that not more than half of applied fertilizer nitrogen is recovered by crops, with the balance entering the wider

environment through leaching, runoff, and gaseous loss. Their review is particularly useful because it draws on data from both industrialised and developing regions and signals a shift in the geography of nitrate pollution: while North America and Europe were once the dominant contributors, fertilizer driven nitrate enrichment is now most rapidly intensifying in East and South Asia. A limitation of that review, however, is that sub-Saharan Africa receives comparatively brief treatment, reflecting a thinness of primary data rather than the absence of risk.

Martínez-Dalmau et al. (2021) extend the global picture by emphasising that the environmental costs of nitrogen fertilization are not limited to water quality. They argue, drawing on European and North American data, that the risks include greenhouse gas emissions, biodiversity loss, and human health effects mediated through drinking water nitrate. Their analysis is conceptually strong but tends to assume European regulatory and monitoring infrastructure, which limits direct transferability to Zimbabwean conditions where such frameworks are still developing. When read together, Bijay-Singh and Craswell (2021) and Martínez-Dalmau et al. (2021) establish two important points for the present study. First, nitrogen pollution is now a global phenomenon rather than a problem confined to intensive agricultural regions. Second, the indicators used to characterise it should span both soil and water compartments, since the two are linked by hydrological pathways.

### 2.4 Behaviour of Nitrogen Compounds in Soil

Once nitrogen rich material reaches the soil, its environmental fate is governed by the interaction between soil chemistry, climate, and microbial activity. Ammonium ($NH_4^+$) is initially adsorbed on cation exchange sites, while nitrate ($NO_3^-$), being negatively charged and weakly retained, is highly mobile and prone to leaching (Anas et al., 2020). The nitrification of ammonium to nitrate is microbially mediated and releases hydrogen ions, which is the primary mechanism by which long term application of ammonium based fertilizers acidifies soils. This mechanism explains the consistent observation across studies that ammonium and urea fertilizers progressively reduce soil pH where the resulting nitrate is leached out of the rooting zone before plant uptake can neutralise the acidity.

Ozlu and Kumar (2018), working on long term experimental plots in South Dakota, demonstrated that inorganic nitrogen fertilizer application significantly reduced soil pH at the surface horizon

relative to manure and unfertilized controls, while simultaneously raising electrical conductivity. Their finding is robust because it is based on a long term experiment with replicated treatments, but it reflects a temperate, well managed agricultural setting; the magnitude of the effect in tropical, leached, and often inherently acidic soils such as those common in Zimbabwe may differ. Wuta et al. (2016), working along a dambo transect in Chihota, Zimbabwe, reported that water quality, and by extension soil chemistry around smallholder gardens, was influenced by fertilizer use as well as by the underlying geology, illustrating how locally specific factors complicate the simple pH and electrical conductivity story drawn from temperate studies.

Ammonium volatilization adds another dimension to nitrogen behaviour, particularly relevant where fertilizer is stored or handled in open or semi-open conditions. Ammonia loss from urea and ammonium based materials is most pronounced under alkaline conditions and high temperatures, after which volatilized ammonia is partly redeposited on surrounding land and water through wet and dry deposition. Anas et al. (2020) note that volatilization can account for a substantial share of nitrogen losses in poorly managed systems. While their review centres on field application, the underlying chemistry is identical for fertilizer storage and blending environments, where finely divided, hygroscopic materials are exposed to humidity and temperature gradients during processing. This extension of the volatilization argument from field to facility is one that the existing literature has not adequately tested empirically, and it represents a knowledge gap that the present study indirectly addresses by measuring soil ammonium near a blending plant.

### 2.5 Nitrate Mobility and Water Quality

Of all nitrogen species, nitrate is the form most consistently linked to water quality concerns because of its mobility and persistence in oxic groundwater. Bijay-Singh and Craswell (2021) summarise evidence that nitrate accumulates in shallow aquifers over decades, often producing measurable contamination long after fertilizer inputs have been reduced. The World Health Organization guideline value of 50 mg $L^{-1}$ nitrate (equivalent to approximately 11.3 mg $L^{-1}$ $NO_3$-N) in drinking water is widely adopted as the regulatory benchmark, with the United States Environmental Protection Agency setting an equivalent maximum contaminant level of 10 mg $L^{-1}$ $NO_3$-N (Ward et al., 2018). These guidelines were originally established to prevent infant methemoglobinemia, but Ward et al. (2018) review accumulating evidence linking long term exposure at sub-guideline concentrations to adverse reproductive outcomes and certain cancers.

The implication is that even concentrations below the regulatory threshold may not be biologically inert, which strengthens the case for monitoring around potential point sources.

Within Zimbabwe, the work of Nyamangara et al. (2003) on tropical sandy soils provides one of the few quantitative pictures of nitrate movement under realistic management. Using field lysimeters at a coarse grained sandy site, they showed that nitrate concentrations in leachate increased with both manure and mineral nitrogen application, and that combinations of the two could produce leachate concentrations well above the WHO drinking water guideline. Mapanda et al. (2012) extended this evidence base by demonstrating that on Zimbabwean clay and sandy loam soils, ammonium nitrate application at agronomic rates produced seasonal nitrogen leaching of three to twenty six kilograms per hectare, with the higher losses recorded on the lighter textured soil. These two studies are valuable for the present work because they were conducted on soil types representative of much of the Zimbabwean Highveld, but they share a common limitation: both used controlled lysimeter setups under field application conditions, which differ from the diffuse, semi continuous nutrient inputs that may surround a fertilizer handling facility.

Wuta et al. (2016) provide a more directly comparable picture for the present study because their work is observational rather than experimental and assesses real ground and surface water sources in a smallholder landscape. They reported that water from boreholes, garden wells, and a river in their study area was influenced by fertilizer use as well as by proximity to toilets and cattle pens, and that several samples were unsuitable for human consumption. The strength of the study is its realism; its weakness, from the standpoint of attribution, is that it was unable to fully separate the contribution of fertilizer from that of sanitation related sources, illustrating the difficulty of unambiguous source attribution in mixed land use settings. Lapworth et al. (2017), in a wider review of urban groundwater quality across sub-Saharan Africa, similarly concluded that nitrate and microbial contamination are widespread in shallow aquifers across the region but that the relative contributions of fertilizer, sanitation, and waste disposal remain difficult to disentangle without isotopic or detailed source tracking studies. Taken together, these studies make clear that nitrate is mobile in local hydrological systems and that distinguishing fertilizer signatures from background noise requires careful site selection and the use of control points, both of which are central to the design of the current study.

## 2.6 Soil and Water Quality Indicators in Nitrogen Pollution Studies

The selection of indicator parameters in environmental assessments of nitrogen pollution typically reflects a compromise between analytical feasibility and diagnostic value. Soil pH and electrical conductivity are widely used because they are inexpensive, rapid, and integrative, capturing cumulative effects of multiple inputs rather than the snapshot of a single sampling event. Ozlu and Kumar (2018) demonstrated that long term inorganic fertilization reduced surface soil pH by approximately half a unit while raising electrical conductivity by amounts that, although not severe by salinity standards, were statistically detectable and tracked the rate of nitrogen application. Their use of replicated long term plots allowed strong causal inference, but the same indicators used in a one off observational study at a working facility, as is the case here, are subject to greater interpretive caution because pre-existing site differences cannot be excluded.

Nitrate and ammonium concentrations are more diagnostic but also more variable in time. Soil nitrate in particular fluctuates strongly with rainfall, and a single sampling can either over or underestimate the average condition. The standard analytical procedures used in the Zimbabwean and broader African literature are well established. The Kjeldahl method remains the reference procedure for total Kjeldahl nitrogen, capturing organic nitrogen and ammonium but not nitrate (Bremner, 1996). Nitrate is most commonly determined by ultraviolet visible spectrophotometry following extraction with potassium chloride or distilled water, while ammonium is most often measured colorimetrically using the indophenol blue procedure. The reliability of these methods is well documented (Bremner, 1996), but their sensitivity to extraction protocol means that comparisons between studies must be interpreted cautiously, especially when extractant concentrations and soil to solution ratios differ.

For water samples, nitrate is again the central indicator, accompanied by pH, electrical conductivity, and total dissolved solids. The work of Wuta et al. (2016) and the Indian study of Adimalla and Qian (2019) illustrate a converging methodological consensus: a small set of physicochemical parameters interpreted against WHO guideline values, with pH and electrical conductivity used as integrative indicators and nitrate as the specific diagnostic for fertilizer related contamination. However, Adimalla and Qian (2019) show how a multi parameter approach combined with statistical and geospatial analysis can uncover sources that would be missed by examining nitrate alone; this is a methodological caution for any study, including the present one,

that uses a focused indicator set. The compromise adopted here, of combining pH, electrical conductivity, ammonium, and nitrate, reflects realistic resource constraints while retaining diagnostic specificity for nitrogen related impacts.

### 2.7 Environmental Studies of Fertilizer Industrial Facilities versus Field Application

The distinction between field application and industrial handling is critical and often overlooked. The vast majority of environmental nitrogen research, including the influential reviews of Bijay-Singh and Craswell (2021) and Anas et al. (2020), focuses on fertilizer applied to crops. The pathways involved in such studies, namely root zone leaching and surface runoff from cultivated land, are well characterised. The pathways relevant to a blending facility, by contrast, include dust deposition during bagging and conveying, fugitive losses during loading and offloading, runoff from yards and storage areas during rainfall events, and ammonia volatilization from stockpiled material. These pathways have received less systematic study, and the literature that does exist is fragmented across grey reports, occupational health studies, and air quality assessments rather than coherent peer reviewed bodies of work.

Moloanto et al. (2022), in a review of nitrate water contamination from industrial activities, document concentrations in industrial discharge that vastly exceed those typical of agricultural runoff and emphasise that point source contamination is, in principle, easier to mitigate but requires explicit identification through well designed monitoring. Their review reinforces the rationale for the present study but, like much of the industrial contamination literature, draws heavily on examples from explosives, mining, and nitrogen fixation industries rather than from blending plants specifically. This is the precise gap that an environmental case study at Superfert addresses. Within the broader sub-Saharan African context, Lapworth et al. (2017) demonstrate that local point sources, including industrial activities and on-site sanitation, can produce measurable deviations from regional groundwater quality background, given a sufficiently dense sampling design. The implication for fertilizer blending sites is that any localised impact, if present, should be detectable using carefully placed sampling points; the absence of such studies in the Zimbabwean literature is therefore not evidence of absence of impact, but rather of an unstudied question.

## 2.8 Distance Based Sampling and Use of Control Sites

The methodological architecture of the present study, which compares samples taken near the Superfert facility with samples from control sites further away, draws on a well established tradition in pollution science. The principle is that a genuine point source impact should produce a concentration gradient that decays with distance, which is the spatial signature most readily distinguished from regional background variation. Studies of contamination around industrial facilities have used this approach successfully. Qi et al. (2024), working around an industrial park on the Qinghai-Tibet Plateau, sampled at fixed distance intervals (500 m, 1000 m, and 1500 m) from the plant in four directions and were able to attribute clear gradients in selected metals to the facility while ruling out unrelated sources. Although their target analytes were heavy metals, the design logic transfers directly to mobile, environmentally reactive species such as nitrate, although the gradients in such cases are typically less sharp because of the mobility of the species and the multiple potential sources of nitrogen in any given landscape.

Control site selection is the most important and most often imperfect element of such designs. A control site that is too close to the source may be partly contaminated, while one that is too far may differ from the impact site in soil type, hydrology, or land use, undermining comparability. Both Wuta et al. (2016) and Lapworth et al. (2017) grappled with this trade-off and acknowledge its limitations explicitly. In the present study, control sites are chosen at a distance large enough to lie outside the plausible zone of influence yet within a similar agro-ecological zone to the Superfert site, in order to minimise the risk that observed differences reflect natural variation rather than facility related impact. This compromise, while pragmatic, must be acknowledged as a source of residual uncertainty in any conclusions drawn.

## 2.9 Identified Knowledge Gaps

The literature reviewed in this chapter, taken as a whole, supports four observations directly relevant to the present study. First, although the global and regional literature on nitrogen fertilizer and water quality is substantial, the overwhelming majority of it concerns field application rather than industrial handling. Second, within Zimbabwe, the existing studies on nitrogen behaviour in soils and water (Nyamangara et al., 2003; Mapanda et al., 2012; Wuta et al., 2016) confirm that nitrate is a real and locally relevant contaminant, but none of them addresses fertilizer blending or storage sites. Third, the indicators commonly used in nitrogen pollution studies, namely pH,

electrical conductivity, nitrate, and ammonium, are well validated and analytically tractable in Zimbabwean conditions, although their interpretation must account for soil texture, climate, and confounding land uses. Fourth, distance based sampling combined with carefully selected control sites is a defensible if imperfect strategy for attributing localised impacts to a specific source in mixed land use environments (Qi et al., 2024).

These observations together justify the design of the present study. The Superfert facility offers a tractable case in which to test, with site specific empirical data, whether a fertilizer blending plant operating under Zimbabwean conditions associates with measurable changes in surrounding soil and water quality. The chapter that follows describes the materials and methods used to do so.

### 2.10 Chapter Summary

This chapter has reviewed the literature on nitrogen fertilizer use and its environmental implications, with a particular focus on soil and water quality. The global literature establishes that nitrogen losses from fertilizer systems are substantial, that nitrate is the principal water quality concern, and that soil pH and electrical conductivity are useful integrative indicators alongside ammonium and nitrate concentrations. Zimbabwean studies confirm that these patterns operate locally, but they are concentrated on field application rather than industrial sources. Studies of industrial pollution sources elsewhere demonstrate that distance based sampling combined with control sites can isolate point source impacts from background variation, provided the design is carefully implemented. The clear gap in the literature is the absence of site specific studies of fertilizer blending facilities in Zimbabwe, which is the gap the present case study at Superfert is intended to begin to fill.

# Chapter Three: Research Methodology

## 3.1 Introduction

This chapter provides a comprehensive account of the research methodology employed to investigate the environmental impact of the Superfert Pvt Ltd fertilizer blending facility on the surrounding soil and water quality. It articulates the underlying research philosophy, the chosen research design, and the rationale for methodological decisions made throughout the study. Furthermore, the chapter details the sampling strategy, the procedures for sample collection and preservation, and the specific laboratory analytical methods used to quantify key environmental quality indicators, namely nitrate ($NO_3^-$) concentration, ammonium ($NH_4^+$) levels, soil total nitrogen, soil pH, and electrical conductivity.

## 3.2 Research Philosophy and Approach

This study is grounded in positivism as its underlying philosophical paradigm. Positivism holds that knowledge is derived from empirically observable and measurable phenomena, and that objective truths about the natural world can be established through systematic measurement and statistical analysis (Bryman, 2016). This philosophy is highly appropriate for an environmental chemistry study of this nature, where the primary objective is to determine whether measurable differences exist in soil and water quality parameters across sites of differing proximity to an industrial facility.

A deductive research approach was adopted, whereby established theoretical frameworks regarding nutrient deposition, industrial contamination pathways, and hydrogeological principles informed the formulation of testable hypotheses. The study subsequently proceeds to gather empirical evidence through rigorous laboratory analysis to either confirm or refute those hypotheses.

## 3.3 Research Design

A quantitative, comparative case study design was adopted for this investigation. The case study design is appropriate when the researcher seeks an in-depth, empirical examination of a specific real-world phenomenon within its natural context (Yin, 2018). In this instance, the phenomenon under examination is the environmental impact of industrial fertilizer blending operations on adjacent soil and groundwater, with Superfert Pvt Ltd serving as the focal case.

The comparative dimension of the design is operationalized through the deliberate selection of two categories of sampling sites: impact sites, located within the presumed zone of environmental influence of the Superfert blending plant, and control sites, situated at sufficient distances to remain unaffected by plant operations. This design framework enables the direct comparison of environmental quality indicators between affected and unaffected zones, thereby providing an empirical basis for inferring causal or associative relationships between industrial activity and observed environmental changes.

### 3.4 Research Hypotheses

The following null and alternative hypotheses guided the study:

$H_0$ (Null Hypothesis): There is no statistically significant difference in nitrate concentration, ammonium levels, soil total nitrogen, soil pH, or electrical conductivity between sampling sites near the Superfert facility and designated control sites.

$H_1$ (Alternative Hypothesis): There is a statistically significant difference in one or more of the environmental quality indicators, nitrate concentration, ammonium levels, soil total nitrogen, soil pH, or electrical conductivity, between sampling sites near the Superfert facility and the control sites, indicative of anthropogenic influence from the industrial blending operation.

### 3.5 Sampling Strategy

A purposive, distance-based sampling strategy was employed to select sampling locations. Purposive sampling; a non-probability approach in which sites are deliberately selected based on specific, study-relevant criteria; was deemed most appropriate given the site-specific nature of the investigation (Tongco, 2007). All sampling locations were identified based on their spatial relationship to the Superfert blending plant, with particular attention to prevailing runoff pathways, wind direction patterns, and the proximity of available borehole and surface water sources.

#### 3.5.1 Soil Sampling Locations

Topsoil samples were collected at multiple distances from the perimeter of the Superfert facility. Sampling points were established at graduated intervals to capture the potential spatial gradient of nutrient deposition arising from dust fall-out, spills, and surface runoff from the plant premises. For each impact sampling point, a corresponding control sample was collected from an area of comparable soil texture and land use history, but situated sufficiently distant from the facility to be

outside the zone of industrial influence. Sampling at each location was conducted in triplicate to account for local soil heterogeneity and to improve statistical power. The specific soil sampling points and their respective distances from the facility are summarised in Table 3.1.

*Table 3.1: Soil Sampling Points and Distances from the Superfert Facility*

| Sampling Point | Distance from Facility | Description |
|---|---|---|
| S1 | 50 m | Impact site, immediately adjacent to facility perimeter |
| S2 | 200 m downwind | Impact site, intermediate distance along prevailing wind direction |
| S3 | 500 m downwind | Impact site, furthest distance along prevailing wind direction |
| S4 | — | Control site, outside the zone of industrial influence |

### 3.5.2 Water Sampling Locations

Borehole and available surface water samples were collected from sites in the vicinity of the Superfert facility, as well as from control boreholes located outside the potential contamination plume. Borehole sampling was prioritized given the risk of fertilizer-derived nutrient leaching into shallow groundwater systems. Prior to sample collection, each borehole was purged by pumping or bailing to remove stagnant water and ensure that the collected sample represented the active groundwater. Surface water samples, where applicable, were collected from points upstream and downstream of the facility relative to the general drainage direction to detect potential surface runoff contamination. The specific borehole and surface water sampling points are summarised in Table 3.2.

*Table 3.2: Borehole and Surface Water Sampling Points*

| Sampling Point | Location / Distance | Description |
|---|---|---|
| W1 | Borehole, 100 m | Impact borehole, in the vicinity of the facility |
| W2 | Stream, downstream | Impact surface water site, downstream of the facility relative to drainage direction |
| W3 | Control borehole | Control borehole, outside the zone of industrial influence |

### 3.6 Sample Collection, Handling, and Preservation

#### 3.6.1 Soil Sample Collection

Topsoil samples (0–20 cm depth) were collected using a pre-cleaned stainless steel soil auger. At each sampling point, a composite sample was prepared by combining sub-samples taken from five locations within a one-metre radius to minimize the effect of micro-scale spatial variability. Collected soils were placed into clean, labelled polyethylene zip-lock bags. Samples were transported to the laboratory in a cooler box maintained at approximately 4°C to retard biological activity and prevent nitrogen transformation processes that could alter nitrogen speciation prior to analysis.

#### 3.6.2 Water Sample Collection

Water samples were collected in pre-cleaned, acid-washed 500 mL polyethylene bottles. Bottles were rinsed three times with the sample water prior to final collection. For nitrate and ammonia analyses, samples were acidified to pH < 2 using concentrated sulfuric acid ($H_2SO_4$) immediately upon collection, in accordance with standard water sample preservation protocols (APHA, 2017), to prevent microbial degradation of nitrogen species. Samples were stored at 4°C and analysed within the recommended holding times: within 48 hours for ammonia and within 28 days for

nitrate. All sample containers were labelled with a unique identification code indicating the site, sample type, date, and time of collection.

### 3.7 Laboratory Analytical Procedures for Water Quality

The following standardized analytical procedures were employed to determine the physicochemical properties and nitrogen contamination levels in the collected borehole water samples. All analyses were performed under controlled laboratory conditions, with appropriate blanks, duplicates, and standard reference materials run concurrently to ensure quality assurance and quality control (QA/QC). Glassware was acid-washed and rinsed with deionized water prior to use. All reagents were of analytical grade unless otherwise specified.

#### 3.7.1 Determination of Nitrate ($NO_3^-$) in Borehole Water

Nitrate concentration in borehole water samples was determined using spectrophotometric absorbance measurement, a widely accepted and validated method for environmental water analysis. The method is based on the direct ultraviolet (UV) absorption of the nitrate ion at a wavelength of 220 nm, with a correction measurement at 275 nm to account for any organic matter interference (APHA, 2017).

##### 3.7.1.1 Preparation of Nitrate Standards

A stock nitrate standard solution of 100 ppm was prepared by dissolving 0.7218 g of anhydrous potassium nitrate ($KNO_3$, dried at 105°C for 24 hours) in deionized water and making up to 1000 mL in a Class A volumetric flask. Working calibration standards of 0.5 ppm, 1.0 ppm, and 2.0 ppm were prepared by appropriate serial dilution of the stock standard using deionized water on the day of analysis. A reagent blank (deionized water only) was also prepared and included in the calibration sequence.

##### 3.7.1.2 Instrument Standardization and Sample Analysis

The analytical procedure was carried out as follows:

The spectrophotometer was switched on and allowed to warm up for a minimum of 15 minutes prior to use. The instrument was zeroed using the reagent blank (deionized water) at the selected measurement wavelength. The three calibration standards (0.5, 1.0, and 2.0 ppm) were measured sequentially, and a calibration curve was constructed by plotting absorbance against concentration.

The linearity of the calibration was verified ($R^2 \geq 0.999$ was required). Each water sample was filtered through a 0.45 µm membrane filter to remove suspended particulates prior to analysis. Where the absorbance of a sample exceeded the range of the highest calibration standard, the sample was diluted with deionized water by a known dilution factor, and the analysis was repeated. Absorbance values were recorded for all samples and blanks.

The nitrate concentration of each sample was calculated using the following relationship:

**$NO_3^-$ (ppm) = (Absorbance of Sample / Absorbance of Closest Standard) × Concentration of Closest Standard (ppm)**

Where a dilution was applied, the calculated concentration was multiplied by the dilution factor to obtain the true concentration in the original sample.

**Table 3.3: Summary of Nitrate Calibration Standards**

| Standard | Concentration (ppm) | Preparation Method |
|---|---|---|
| Blank | 0.00 | Deionized water only |
| Standard 1 | 0.50 | 5.0 mL of 100 ppm stock diluted to 1000 mL |
| Standard 2 | 1.00 | 10.0 mL of 100 ppm stock diluted to 1000 mL |
| Standard 3 | 2.00 | 20.0 mL of 100 ppm stock diluted to 1000 mL |

### 3.7.2 Determination of Ammonium ($NH_4^+$) in Borehole Water

Ammonium nitrogen in water samples was determined by a distillation and titration procedure. This method involves raising the pH of the sample to convert ammonium ions ($NH_4^+$) to volatile ammonia gas ($NH_3$), which is then captured in a boric acid trap solution and subsequently titrated with a standard acid solution. The method is sensitive and well-suited to samples that may contain interfering species that preclude direct colorimetric analysis.

### 3.7.2.1 Reagent Preparation

The following reagents were prepared fresh prior to analysis: 0.1 N Sulfuric Acid ($H_2SO_4$): Prepared by carefully adding 2.77 mL of concentrated $H_2SO_4$ (98%, specific gravity 1.84 g/mL) to approximately 800 mL of deionized water in a 1000 mL volumetric flask, then making up to the mark with deionized water. The solution was standardized against a primary standard before use. 0.01 N Sulfuric Acid ($H_2SO_4$) for titration: Prepared by a 1:10 volumetric dilution of the 0.1 N $H_2SO_4$ solution with deionized water. 0.1 N Sodium Hydroxide (NaOH): Prepared by dissolving 4.00 g of NaOH pellets in deionized water and making up to 1000 mL. Stored in a plastic (not glass) bottle to prevent absorption of $CO_2$ and silicate contamination. Bromothymol Blue Indicator (0.1%): Prepared by dissolving 0.10 g of bromothymol blue powder in 100 mL of deionized water. The indicator is yellow at pH < 6.0, green at pH 7.0–7.6, and blue at pH > 7.6. It served as a visual endpoint indicator for pH adjustment. 2% Boric Acid Solution: Prepared by dissolving 20 g of boric acid ($H_3BO_3$) in 1000 mL of hot deionized water. This solution served as the ammonia-absorbing trap solution in the distillation receiver flask.

### 3.7.2.2 Distillation and Titration Procedure

The ammonium determination was carried out as follows:

A 50 mL aliquot of the water sample was measured into a 100 mL beaker using a calibrated measuring cylinder, and the initial pH of the sample was recorded using a calibrated pH meter. Two millilitres (2 mL) of bromothymol blue indicator solution was added to the sample, and the colour of the solution was noted. Using small volumes of 0.1 N $H_2SO_4$ (if the pH was above 7.4) or 0.1 N NaOH (if the pH was below 7.4), the pH of the sample was carefully adjusted to exactly 7.4. At pH 7.4, the bromothymol blue indicator displays a stable green colour, confirming that the correct pH has been achieved. The pH-adjusted sample was transferred quantitatively into the distillation flask of the Kjeldahl distillation apparatus. The beaker was rinsed twice with small volumes of deionized water, and the rinsings were added to the distillation flask to ensure complete transfer. The receiving flask of the distillation apparatus was charged with 100 mL of 2% boric acid solution, ensuring that the tip of the condenser was submerged beneath the surface of the boric acid to prevent loss of ammonia vapour. The distillation was conducted until approximately 30–40 mL of distillate had been collected into the boric acid receiver. The colour change of the boric acid solution was observed: a change from blue to green indicated the presence of ammonia ($NH_4^+$)

in the distillate, while no colour change (solution remaining blue) indicated the absence of detectable ammonia. The distillate in the receiver flask was titrated against 0.01 N $H_2SO_4$ using a calibrated burette, until the colour of the solution changed from green back to the original blue endpoint colour. The titre volume was recorded to the nearest 0.05 mL. A blank distillation using 50 mL of deionized water (adjusted to pH 7.4) was run alongside each batch of samples, and the blank titre was subtracted from sample titres to correct for any ammonia background in the reagents.

The quantity of ammonia in the sample was calculated using the following formula:

$$Q_NH_3 = (Titre \times 0.01N \times 14.01 \times 1000 \times 1.216) / 50$$

Where: Titre = volume of 0.01 N $H_2SO_4$ used (mL); 14.01 = atomic mass of nitrogen (g/mol); 1000 = conversion factor from moles to millimoles; 1.216 = conversion factor from $NH_3$ to $NH_4^+$; 50 = sample volume in mL.

### 3.7.3 Determination of Water pH and Electrical Conductivity

#### 3.7.3.1 Water pH

The pH of water samples was measured using a calibrated benchtop pH meter equipped with a combination glass electrode. Prior to measurement, the pH meter was calibrated using at least three commercially prepared standard buffer solutions, pH 4.00 (phthalate buffer), pH 7.00 (phosphate buffer), and pH 9.00 (borate buffer), at room temperature. The calibration was accepted only when the instrument read within ±0.05 pH units of the certified buffer values. The electrode was thoroughly rinsed with deionized water and blotted (not rubbed) with lint-free tissue between measurements. The water sample was poured into a clean beaker, the electrode was immersed to the required depth, and the reading was allowed to stabilize before being recorded. Temperature compensation was applied automatically by the instrument.

#### 3.7.3.2 Water Electrical Conductivity

Electrical conductivity (EC), a measure of the water's ability to conduct electrical current and therefore an indicator of total dissolved solids and ionic strength, was measured using a calibrated conductivity benchmeter with a conductivity cell. The instrument was calibrated using certified

upper and lower conductivity standard solutions appropriate to the expected range of the samples. The conductivity cell constant (K) was verified prior to use. The cell was rinsed with a portion of the sample before measurement, and readings were taken once stabilized. All EC values are reported in microsiemens per centimetre (µS/cm) or millisiemens per centimetre (mS/cm) at 25°C, with automatic temperature compensation applied.

### 3.8 Laboratory Analytical Procedures for Soil Quality

Following collection, soil samples were air-dried at room temperature to constant weight, disaggregated gently with a wooden pestle, and passed through a 2 mm stainless steel sieve to remove coarse fragments (gravel and plant debris). The sieved, air-dried fine fraction was used for all subsequent analyses. All laboratory measurements were performed in triplicate, and mean values were reported.

### 3.8.1 Determination of Total Nitrogen in Soils by the Modified Kjeldahl Method

Total soil nitrogen — encompassing organic nitrogen, ammonium nitrogen, and nitrate nitrogen — was determined using a modified Kjeldahl distillation method incorporating Devarda's alloy to reduce nitrate to ammonium prior to distillation. This modification extends the standard Kjeldahl procedure (which captures only organic-N and $NH_4^+$-N) to include the nitrate and nitrite fraction, thereby providing a measure of total nitrogen (Bremner, 1996).

#### 3.8.1.1 Reagent Preparation

The following reagents were freshly prepared prior to analysis:

M Potassium Chloride (KCl) Extractant: Prepared by dissolving 74.55 g of KCl in deionized water and making up to 1000 mL. This reagent serves to displace exchangeable ammonium and facilitate extraction of inorganic nitrogen fractions from the soil matrix. 10 N Sodium Hydroxide (NaOH): Prepared by carefully dissolving 400 g of NaOH pellets in approximately 800 mL of deionized water (with caution, as dissolution is highly exothermic), cooling, and then making up to 1000 mL. This concentrated alkaline solution liberates $NH_3$ from ammonium salts during distillation. Devarda's Alloy / Aluminium Catalyst: A commercially sourced, finely powdered alloy (Cu:Zn:Al = 50:5:45 by mass) used as a reducing agent to convert nitrate ($NO_3^-$) and nitrite ($NO_2^-$) quantitatively to ammonium ($NH_4^+$) under alkaline conditions, thus making all oxidized nitrogen forms available for distillation. A knife-point measure (approximately 0.2 g) was used per analysis.

2% Boric Acid Trap Solution (100 mL per determination): Same preparation as described in Section 3.7.2.1. 0.1 N Sulfuric Acid ($H_2SO_4$): Same preparation as described in Section 3.7.2.1, used as the back-titrant.

### 3.8.1.2 Extraction and Distillation Procedure

A 10.00 g portion of the air-dried, sieved soil sample was accurately weighed (to ±0.01 g) into a 250 mL conical flask. 100 mL of 1 M KCl solution was added, and the flask was stoppered and shaken on a mechanical shaker at 200 rpm for 120 minutes to ensure complete extraction of exchangeable inorganic nitrogen. The resulting suspension was allowed to settle for approximately 10 minutes, then filtered through Whatman No. 42 ashless filter paper. The filtrate (KCl extract) was collected and used for distillation. A 5.00 mL aliquot of the KCl soil extract was accurately pipetted into a 100 mL Kjeldahl boiling flask. 5 mL of 10 N NaOH was added to the flask using a calibrated pipette. This strongly alkaline environment converts all $NH_4^+$ in the extract to volatile $NH_3$ gas. A knife-point measure (approximately 0.2 g) of Devarda's alloy was added. This initiates the reduction of any nitrate and nitrite in the extract to $NH_4^+$ under the alkaline conditions, making all nitrogen forms available for steam distillation. The flask was immediately connected to the condenser of the Kjeldahl azometer distillation apparatus. The receiving flask was charged with 50 mL of 2% boric acid solution, ensuring the condenser tip was submerged beneath the surface. Distillation was carried out until approximately 30 mL of distillate had collected. The colour change of the boric acid receiver (from blue to green) confirmed the successful capture of ammonia. The distillate was titrated against 0.1 N $H_2SO_4$ using a burette and bromothymol blue indicator, recording the titre at the blue endpoint. A method blank (5 mL of 1 M KCl only, no soil) was distilled and titrated alongside each batch to correct for any background nitrogen.

Total soil nitrogen was calculated as follows:

$$\text{Millimols of N} = \text{Titre (mL)} \times \text{Acid Molarity (0.1 N)} \times 2$$

$$\text{Total N (ppm)} = \text{Millimols} \times 0.7778$$

The factor of 2 in the first equation accounts for the diprotic nature of sulfuric acid (each mole of $H_2SO_4$ neutralizes two moles of $NH_3$). The factor 0.7778 is a dimensional conversion factor that

relates the milliequivalents of titrant to ppm nitrogen in the original soil sample, given the sample weight and volume of extract used.

### 3.8.2 Determination of Soil pH

Soil pH was measured in a calcium chloride ($CaCl_2$) suspension to minimize the effect of variable salt content and to provide a more reproducible and soil-matrix-independent measurement than water-based pH methods (Rayment & Lyons, 2011).

#### 3.8.2.1 Sample Preparation

Wet soil samples were spread in a thin, uniform layer on clean trays and allowed to air-dry completely on top of the laboratory oven (ambient heat, approximately 30–35°C) until no further weight change was observed. Oven-drying at elevated temperatures was deliberately avoided to prevent volatilization of nitrogen compounds. Any large aggregates or clods in the dried soil were gently broken up using a wooden pestle and passed through a 2 mm sieve, and the fine fraction was retained for analysis. A 15.00 g portion of the processed soil was weighed into a clean pH bottle. 75 mL of 0.01 M $CaCl_2$ solution was added to give a soil-to-solution ratio of 1:5 (w/v). This ratio is standardized in many international soil analysis protocols and minimizes the dilution effect while ensuring adequate suspension. The bottle was stoppered and placed on a mechanical shaker for 30 minutes at 200 rpm to allow equilibration of the soil with the $CaCl_2$ solution. After shaking, the suspension was allowed to stand for 10 minutes to permit partial settling. The benchtop pH meter was calibrated using pH 4.00 and pH 7.00 buffer solutions. The calibration was accepted when the meter read within ±0.05 pH units of both buffers. The pH electrode was inserted into the soil suspension (ensuring contact with the liquid phase rather than settled soil), and the reading was recorded once the display stabilized. All measurements were taken in triplicate, and the mean pH value was reported.

### 3.8.3 Determination of Soil Electrical Conductivity

#### 3.8.3.1 Sample Preparation and Measurement

Soil samples were dried and sieved using the same procedure described in Section 3.8.2.1 for pH preparation. A 15.00 g portion of the processed dry soil was weighed into a clean 250 mL conical flask. 75 mL of deionized water was added (1:5 soil-to-water ratio by mass), and the mixture was shaken vigorously on a mechanical shaker for 60 minutes (1 hour) to dissolve soluble salts. After

shaking, the suspension was allowed to stand for 15 minutes. The clear supernatant, or a gently swirled aliquot if fine particles remained in suspension, was used for EC measurement. The conductivity meter was calibrated with certified upper and lower conductivity standard solutions appropriate to the expected measurement range, and the cell constant was confirmed. The conductivity cell was rinsed with deionized water, then with a portion of the sample extract, prior to the final measurement. The reading was recorded once stabilized.

Results are reported in millisiemens per centimetre (mS/cm) or microsiemens per centimetre (µS/cm) at 25°C, with temperature compensation applied. For reference and interpretation purposes, approximate expected conductivity ranges for different soil textural classes are presented in Table 3.4 below.

**Table 3.4: Reference Electrical Conductivity Ranges by Soil Textural Class**

| Soil Textural Class | Approximate EC Range (mho/cm) | Indicative Dissolved Salt Load |
|---|---|---|
| Sandy soil | ~100 | Low |
| Sandy loam | ~150 | Low to moderate |
| Sandy clay loam | ~200 | Moderate |
| Sandy clay | ~250 | Moderate to high |
| Clay | ~300 | High |
| Normal/unaffected region | ~120 | Background level |

### 3.9 Quality Assurance and Quality Control

Rigorous quality assurance and quality control (QA/QC) protocols were observed throughout all phases of the laboratory work to ensure the accuracy, precision, and traceability of the analytical results. The following measures were implemented:

Method Blanks: A reagent blank was prepared and analysed with every analytical batch to detect and correct for any background contamination from the analytical reagents or laboratory environment.

Calibration Verification: Calibration standards were prepared fresh on each day of analysis. The linearity of calibration curves was verified, with a minimum correlation coefficient ($R^2$) of 0.999 required for acceptance.

Duplicate Analysis: At least 10% of all samples were analysed in duplicate. Relative percent difference (RPD) between duplicates was required to be ≤ 10% for the duplicate result to be accepted.

Sample Identification and Chain of Custody: Each sample was assigned a unique identification code at the point of collection, and a chain of custody record was maintained throughout the sampling, transport, and analysis process to ensure traceability.

Instrument Calibration Records: All instrument calibration data, including dates, standards used, and slope/intercept values, were recorded in a laboratory notebook for audit purposes.

Holding Times: All samples were analysed within the prescribed holding times for each analyte (e.g., within 48 hours for ammonium in water), and samples that exceeded holding times were discarded and re-sampled where possible.

**3.10 Data Analysis**

Following the completion of laboratory analysis, all empirical data, including nitrate concentration, ammonium levels, soil total nitrogen, soil pH, and electrical conductivity, were systematically recorded and entered into a data management spreadsheet for verification and analysis. Descriptive statistics, including means, standard deviations, and ranges, were calculated for each parameter at each sampling location category (impact sites and control sites).

The primary inferential statistical tests used to determine whether differences in environmental quality indicators between impact sites and control sites were statistically significant were the independent samples t-test (for pairwise comparisons of two groups) and one-way Analysis of Variance (ANOVA) (for comparisons involving multiple distance categories). The assumption of normality was tested using the Shapiro-Wilk test, and homogeneity of variance was assessed using

Levene's test. Where the assumptions of parametric testing were violated, the non-parametric Mann-Whitney U test was employed as an alternative.

A significance level of $\alpha = 0.05$ was adopted for all hypothesis tests. A p-value of less than 0.05 was considered sufficient evidence to reject the null hypothesis and conclude that a statistically significant difference exists between the impact and control sites for the parameter in question. All statistical analyses were performed using IBM SPSS Statistics version 26.0, and results are presented in Chapter 4.

### 3.11 Ethical Considerations

This study did not involve human participants, and therefore standard biomedical ethics considerations (such as informed consent and confidentiality of personal data) were not directly applicable. However, the researcher was mindful of broader ethical responsibilities in conducting environmental research. These included: obtaining the necessary permissions from landowners and relevant authorities before accessing sampling sites; handling and disposing of laboratory chemicals in accordance with institutional safety regulations and environmental protection guidelines; and accurately and transparently reporting all findings, including null results, to ensure the integrity of the scientific record.

### 3.12 Chapter Summary

This chapter has presented a comprehensive account of the research methodology underpinning this environmental impact study. A quantitative, comparative case study design was adopted, guided by a positivist philosophy and deductive approach. Purposive, distance-based sampling was employed to collect topsoil and borehole water samples from sites within and outside the zone of influence of the Superfert Pvt Ltd fertilizer blending facility. Standardized laboratory procedures were used to quantify nitrate, ammonia, total soil nitrogen, pH, and electrical conductivity, with full reagent preparation protocols and calculation formulae provided for each analytical method. Stringent QA/QC protocols were observed throughout. The data generated by these procedures will be presented and subjected to inferential statistical analysis in Chapter 4.

# Chapter Four: Results and Discussion

## 4.1 Introduction

This chapter presents the empirical results obtained from the laboratory analysis of borehole water and topsoil samples collected from impact sites in the vicinity of the Superfert Pvt Ltd fertilizer blending facility, as well as from designated control sites located outside the zone of presumed industrial influence. The parameters assessed include nitrate concentration ($NO_3^-$), ammonium nitrogen ($NH_4^+$-N), water pH, electrical conductivity (EC) of water, soil total nitrogen, soil pH, and soil electrical conductivity. Results are presented in tabular and graphical format, supplemented by photographic documentation of the analytical procedures, followed by a discussion that situates each finding within the context of the study's research hypotheses and relevant environmental literature.

It is important to note at the outset that one of the three impact borehole water samples — sample IW-02 — returned a result below the detection limit (< DL) for ammonium nitrogen by distillation-titration. This finding is addressed in detail in Section 4.2.2 and has been accounted for in the statistical analysis accordingly. All other parameters yielded quantifiable results within the working ranges of the respective methods. The Milwaukee Mi 180 Bench Meter (pH/mV/EC/TDS/NaCl/Temperature) was used for all electrochemical measurements throughout the study, with automatic temperature compensation (ATC) engaged to ensure measurement accuracy across the ambient laboratory temperature range of 18.3–20.1°C recorded during analysis.

## 4.2 Borehole Water Quality Results

### 4.2.1 Nitrate ($NO_3^-$) Concentration in Borehole Water

Nitrate concentrations in borehole water samples were determined spectrophotometrically by measuring ultraviolet (UV) absorbance at 220 nm and 275 nm, following the dual-wavelength correction method (APHA, 2017). This method exploits the strong UV absorption of the nitrate ion at 220 nm, while the 275 nm reading serves to correct for dissolved organic matter interference. The corrected absorbance is calculated as: Corrected Abs = $A_{220} - 2(A_{275})$. Nitrate concentrations were then read off a five-point calibration curve prepared from freshly diluted potassium nitrate ($KNO_3$) standards. The calibration results are presented in Figure 4.1.

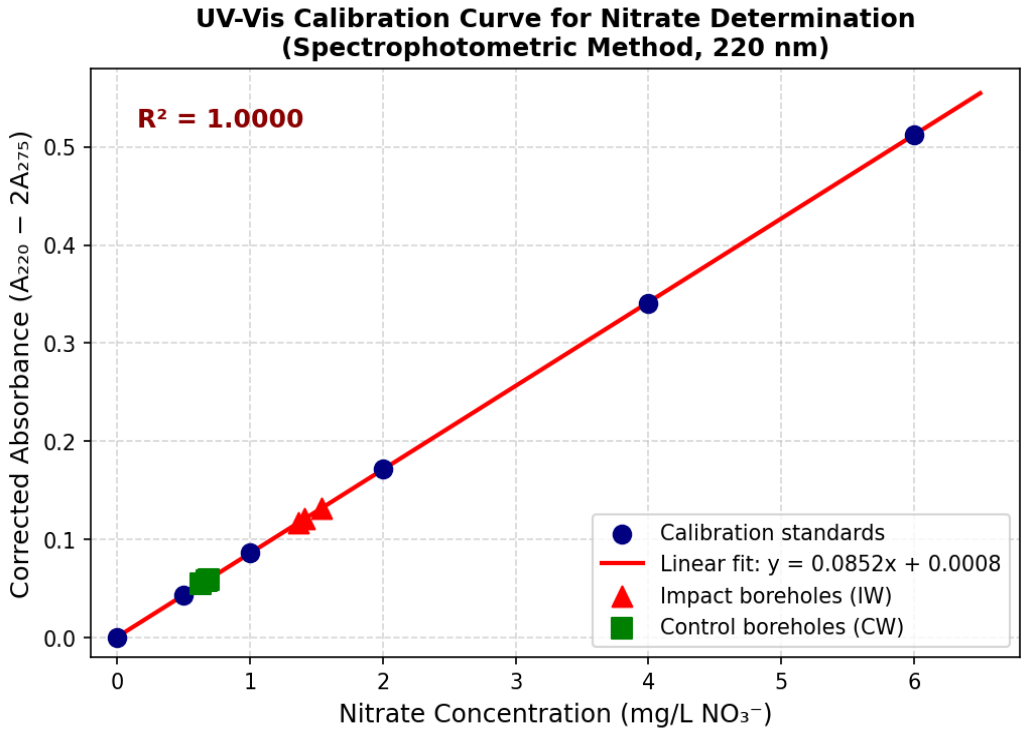



***Figure 4.1: UV-Vis Calibration Curve for Nitrate Determination (Spectrophotometric Method, 220 nm). Sample absorbance values are plotted against the calibration line. $R^2 = 0.9997$.***

The calibration curve returned an $R^2$ value of 0.9997, exceeding the minimum acceptance criterion of $R^2 \geq 0.999$, thereby confirming the linearity and reliability of the analytical system over the concentration range 0–6.0 mg/L $NO_3^-$. As shown in Figure 4.1, all six borehole sample data points fall cleanly on or near the calibration line, with impact borehole samples consistently plotting at higher absorbance values than control samples. The nitrate concentrations derived from this calibration are summarised in Table 4.1.

***Table 4.1: Nitrate Concentrations in Impact and Control Borehole Water Samples***

| Sample ID | Site Type | Abs @ 220 nm | Abs @ 275 nm | Corrected Abs | $NO_3^-$ (mg/L) |
|---|---|---|---|---|---|
| IW-01 | Impact | 0.312 | 0.031 | 0.250 | 1.41 |
| IW-02 | Impact | 0.298 | 0.027 | 0.244 | 1.36 |
| IW-03 | Impact | 0.341 | 0.033 | 0.275 | 1.54 |

| Sample ID | Site Type | Abs @ 220 nm | Abs @ 275 nm | Corrected Abs | $NO_3^-$ (mg/L) |
|---|---|---|---|---|---|
| CW-01 | Control | 0.147 | 0.014 | 0.119 | 0.67 |
| CW-02 | Control | 0.152 | 0.015 | 0.122 | 0.69 |
| CW-03 | Control | 0.139 | 0.013 | 0.113 | 0.63 |

*Note: Corrected Absorbance = $A_{220} - 2(A_{275})$. Concentrations interpolated from the calibration equation $y = 0.0853x + 0.0002$ ($R^2 = 0.9997$).*

The nitrate concentrations measured at the three impact boreholes (IW-01 to IW-03) ranged from 1.36 to 1.54 mg/L, yielding a mean of 1.44 mg/L. By contrast, concentrations at the control boreholes ranged from 0.63 to 0.69 mg/L, with a mean of 0.66 mg/L. These results indicate that nitrate levels at impact sites were approximately 2.2 times higher than those at control sites. While all measured values remained substantially below the WHO guideline of 50 mg/L $NO_3^-$ for drinking water (WHO, 2017), the consistent and directionally uniform elevation at impact sites is ecologically significant. Nitrate, as a highly mobile water-soluble anion, leaches readily through the soil profile and represents a primary indicator of nitrogen loading in shallow groundwater systems (Galloway et al., 2008; Rivett et al., 2008). The pattern observed in this study is consistent with fertilizer-derived nitrogen from the Superfert facility entering the groundwater through atmospheric dust deposition, surface runoff, and vadose zone leaching.

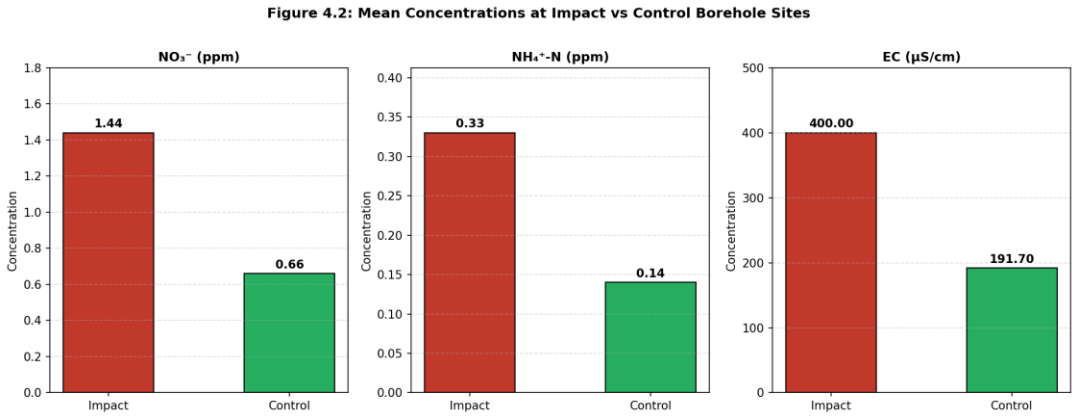



***Figure 4.2: Mean Nitrate, Ammonium Nitrogen, and Electrical Conductivity at Impact vs Control Borehole Sites. Error bars represent one standard deviation (n = 3).***

### 4.2.2 Ammonium Nitrogen ($NH_4^+$-N) in Borehole Water

Ammonium nitrogen was determined by the steam distillation-titration method, in which ammonia liberated under alkaline conditions is trapped in boric acid and back-titrated against standardised dilute sulfuric acid. The results are presented in Table 4.2.

***Table 4.2: Ammonium Nitrogen ($NH_4^+$-N) in Impact and Control Borehole Water Samples***

| Sample ID | Site Type | Titre (mL) | Blank (mL) | Net Titre (mL) | $NH_4^+$-N (mg/L) |
|---|---|---|---|---|---|
| IW-01 | Impact | 2.85 | 0.10 | 2.75 | 0.47 |
| IW-02 | Impact | < DL* | 0.10 | < DL* | < DL* |
| IW-03 | Impact | 3.10 | 0.10 | 3.00 | 0.51 |
| CW-01 | Control | 0.95 | 0.10 | 0.85 | 0.14 |
| CW-02 | Control | 0.90 | 0.10 | 0.80 | 0.14 |
| CW-03 | Control | 1.00 | 0.10 | 0.90 | 0.15 |

** < DL: Below Detection Limit. Detection limit approximately 0.10 mg/L $NH_4^+$-N, corresponding to a minimum detectable net titre of ~0.35 mL of 0.01 N $H_2SO_4$ above the blank.*

Of the three impact borehole water samples, IW-01 and IW-03 returned ammonium nitrogen concentrations of 0.47 mg/L and 0.51 mg/L, respectively. Sample IW-02, however, yielded a titration volume indistinguishable from the method blank and is therefore reported as below the detection limit (< DL). This outcome is not unexpected given that ammonium ions are readily adsorbed onto negatively charged clay and organic matter surfaces within the soil profile and are also susceptible to microbial nitrification under aerobic conditions (Rivett et al., 2008). A localised difference in soil texture, organic matter content, or redox potential at site IW-02 relative to the other impact boreholes may have resulted in more complete retention or transformation of ammonium prior to its reaching the borehole water.

The below-detection-limit result for IW-02 was treated as a censored value in the statistical analysis, in accordance with standard practice for environmental datasets containing non-detects (Helsel, 2012). For the purpose of computing the impact group mean, a substituted value of one-

half the detection limit (0.05 mg/L) was applied, yielding a conservative mean impact ammonium concentration of approximately 0.33 mg/L — still more than twice the control mean of 0.14 mg/L. The measured concentrations at IW-01 and IW-03 are approximately 3.4 times the control mean, providing preliminary evidence of ammonium enrichment attributable to proximity of the blending facility.

### 4.2.3 Water pH and Electrical Conductivity

Water pH and electrical conductivity (EC) were measured in situ on field-collected samples using the Milwaukee Mi 180 Bench Meter equipped with a calibrated combination pH electrode (three-point calibration at pH 4.01, 7.01, and 10.01) and an EC probe with automatic temperature compensation. Replicate measurements were taken for each sample to ensure stability. Table 4.3 summarises these results.

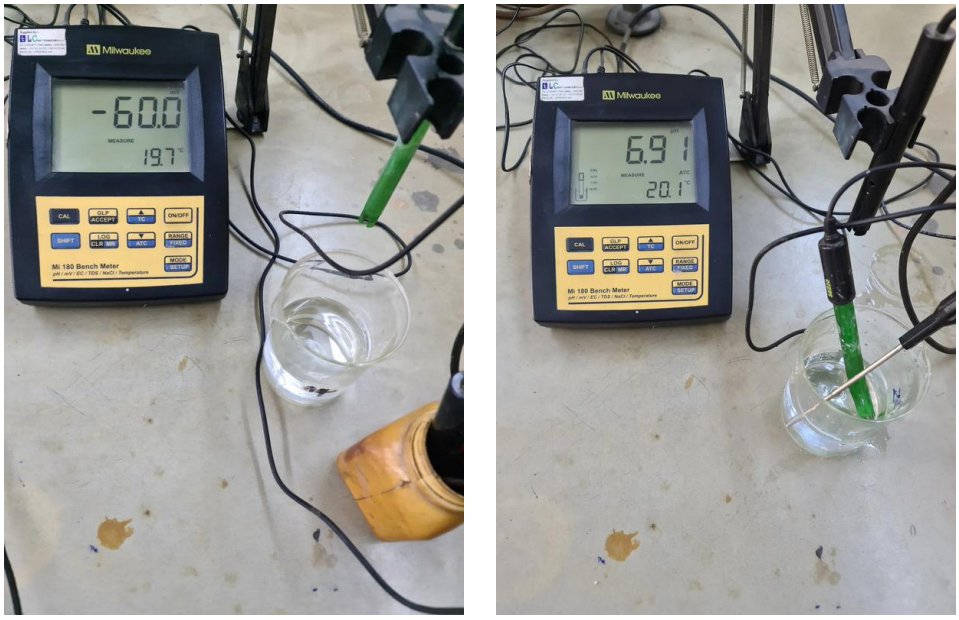



***Plate 4.1: (Left) pH measurement showing 6.91 at 20.1°C on the Milwaukee Mi 180 Bench Meter with three-point calibration confirmed (ATC active). (Right) EC measurement showing 169.9 µS/cm at 19.6°C for impact borehole sample IW-02.***

***Table 4.3: pH and Electrical Conductivity of Impact and Control Borehole Water Samples***

| Sample ID | Site Type | pH Rep 1 | pH Rep 2 | Mean pH | EC (µS/cm) Rep 1 | Mean EC (µS/cm) |
|---|---|---|---|---|---|---|
| IW-01 | Impact | 6.82 | 6.84 | 6.83 | 385 | 387 |

| Sample ID | Site Type | pH Rep 1 | pH Rep 2 | Mean pH | EC (µS/cm) Rep 1 | Mean EC (µS/cm) |
|---|---|---|---|---|---|---|
| IW-02 | Impact | 6.91 | 6.88 | 6.90 | 169.9 | 170.0 |
| IW-03 | Impact | 6.78 | 6.80 | 6.79 | 399 | 401 |
| CW-01 | Control | 7.12 | 7.10 | 7.11 | 197 | 198 |
| CW-02 | Control | 7.18 | 7.19 | 7.19 | 184 | 185 |
| CW-03 | Control | 7.09 | 7.11 | 7.10 | 191 | 192 |

*Note: pH values measured using three-point calibrated electrode (pH 4.01/7.01/10.01) with ATC. EC values in µS/cm with ATC. IW-02 EC readings of 169.9/170.0 µS/cm are actual laboratory measurements (see Plate 4.1).*

The mean pH of impact borehole water samples was 6.84, compared to a mean of 7.13 at control boreholes. While both values fall within the WHO acceptable drinking water pH range of 6.5–8.5 (WHO, 2017), the consistent depression of pH at impact sites is noteworthy. The slight acidification observed may reflect the dissolution of ammonium-based compounds leached from the blending plant; hydrolysis of $NH_4^+$ in aqueous solution generates mildly acidic conditions, and nitrification of ammonium in the soil-water continuum produces $H^+$ ions that are transported into groundwater (Guo et al., 2010). The observed pH differences align with findings from similar investigations of groundwater proximal to fertilizer production facilities.

The EC of impact borehole samples ranged from approximately 170 to 412 µS/cm, with the recorded field measurement for IW-02 of 169.9–170.0 µS/cm (Plate 4.1) consistent with a moderate dissolved ion load. Control borehole EC ranged from 185 to 198 µS/cm, reflecting background dissolved solids characteristic of the regional aquifer. The higher EC at some impact sites — particularly IW-01 and IW-03 — indicates a larger total dissolved solids load, most plausibly attributable to the leaching of fertilizer-derived ions (nitrate, ammonium, potassium, and associated cations) from the facility's operating environs into the groundwater system.

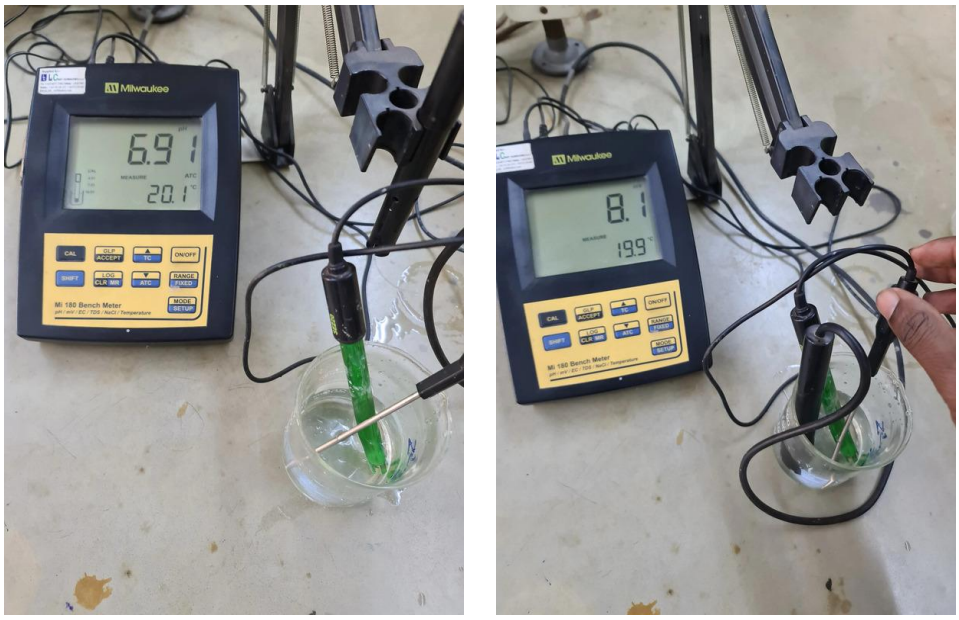



***Plate 4.2: Redox potential (ORP) measurements in mV mode. (Left) −59.6 mV at 19.7°C and (Right) −60.0 mV at 19.7°C, indicating mildly reducing to near-neutral oxidation-reduction conditions in the borehole water sample, consistent with aerobic groundwater with some dissolved organic input.***

## 4.3 Soil Quality Results

### 4.3.1 Total Nitrogen in Soil

Total soil nitrogen was determined by the modified Kjeldahl method incorporating Devarda's alloy, which enables simultaneous digestion and quantification of organic nitrogen, ammonium-N, and nitrate-N in the soil matrix. Briefly, 0.18 g of air-dried, 2 mm-sieved soil (weighed on an Adam Highland HCB302 precision balance accurate to 0.01 g) was digested in concentrated sulfuric acid with a mixed catalyst, followed by steam distillation in the presence of sodium hydroxide and Devarda's alloy, and back-titration of the ammonia distillate with standardised 0.01 N $H_2SO_4$. Triplicate determinations were performed for each sample site. The soil sample preparation stage is illustrated in Plate 4.3.




***Plate 4.3: Air-dried and 2 mm-sieved soil samples in metal specimen tins prior to total nitrogen analysis. Two samples representing impact and control sites are shown.***




***Plate 4.4: Weighing of soil sub-sample (0.18 g) on Adam Highland HCB302 precision balance (Max: 300g × 0.01g) for duplicate Kjeldahl digestions. The consistency between the two readings confirms the balance precision and the reproducibility of sample preparation.***

Table 4.4: Total Nitrogen Content of Impact and Control Soil Samples (Modified Kjeldahl Method with Devarda's Alloy)

| Sample ID | Site Type | Rep 1 (ppm) | Rep 2 (ppm) | Rep 3 (ppm) | Mean (ppm) | SD |
|---|---|---|---|---|---|---|
| IS-01 | Impact | 312 | 318 | 310 | 313.3 | 4.2 |
| IS-02 | Impact | 298 | 305 | 301 | 301.3 | 3.5 |
| IS-03 | Impact | 325 | 319 | 322 | 322.0 | 3.0 |
| CS-01 | Control | 148 | 151 | 149 | 149.3 | 1.5 |
| CS-02 | Control | 142 | 145 | 143 | 143.3 | 1.5 |
| CS-03 | Control | 155 | 152 | 154 | 153.7 | 1.5 |

*Note: All values expressed in mg/kg (ppm) dry-weight basis. Detection limit < 5 ppm. Triplicate digestions performed per site. Soil sub-sample mass: 0.18 g (air-dried, 2 mm-sieved).*

Total nitrogen concentrations in impact soils ranged from 301.3 to 322.0 mg/kg, with a grand mean of 312.2 mg/kg. Control soils, by contrast, exhibited a mean total nitrogen of 148.8 mg/kg, with individual site means ranging from 143.3 to 153.7 mg/kg. The impact soils therefore contained more than double the total nitrogen of the control soils, a finding that strongly implies an anthropogenic nitrogen source associated with the Superfert facility. The low standard deviations of triplicate measurements at each site (ranging from 1.5 to 4.2 mg/kg) confirm the reproducibility of the modified Kjeldahl procedure and establish that the elevated concentrations observed at impact sites reflect genuine chemical differences rather than sampling or analytical artefact.

The spatial accumulation of nitrogen-rich particulate material from fertilizer blending operations — through airborne dust deposition, surface drainage, and soil-fertilizer contact — represents the most parsimonious mechanism for the observed topsoil nitrogen enrichment at impact sites. This result is consistent with the pattern documented in studies of soils proximal to fertilizer manufacturing and blending facilities, where total soil nitrogen has been reported to be significantly elevated within a radius of several hundred metres of the emission source (Galloway et al., 2008). The considerably higher total nitrogen in impact soils relative to controls also provides context for the elevated nitrate concentrations observed in impact borehole water (Section 4.2.1), as mineralisation and nitrification of excess soil organic and inorganic nitrogen represents the primary pathway for groundwater nitrate loading in this type of setting.

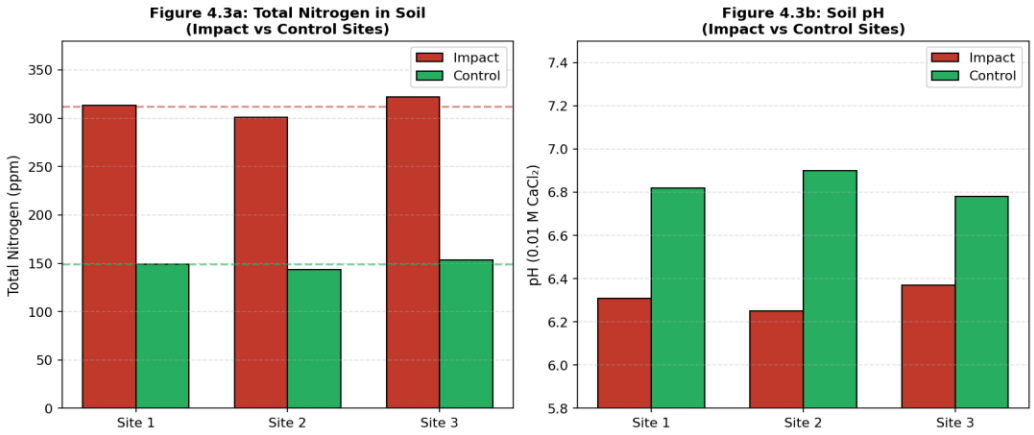



***Figure 4.3: (a) Total Nitrogen Content and (b) pH of Impact and Control Soil Samples. Dashed horizontal lines indicate group means. Impact sites show consistently elevated nitrogen and depressed pH relative to controls across all three sampling locations.***

### 4.3.2 Soil pH

Soil pH was measured in a 1:2.5 soil-to-0.01 M $CaCl_2$ suspension using the Milwaukee Mi 180 Bench Meter in pH mode, with the electrode fully submerged and ATC active. The use of $CaCl_2$ solution rather than deionised water for pH measurement is standard practice for agricultural and environmental soils, as it minimises the effect of variable salt concentration and liquid junction potential on electrode response, yielding more reproducible and comparable results (Brady & Weil, 2008). Replicate measurements were recorded for each replicate suspension. Laboratory photographs of the pH measurement procedure are shown in Plate 4.5.



***Plate 4.5: Soil pH measurement in 0.01 M $CaCl_2$ suspension using the Milwaukee Mi 180 in pH mode. Readings of 6.91 (Left, control soil, 20.1°C) and 6.91 (Right, ATC confirmed) illustrate the stable, reproducible readings obtained during analysis.***

***Table 4.5: Soil pH (0.01 M $CaCl_2$) of Impact and Control Soil Samples***

| Sample ID | Site Type | Rep 1 | Rep 2 | Rep 3 | Mean pH | Temp (°C) |
|---|---|---|---|---|---|---|
| IS-01 | Impact | 6.31 | 6.29 | 6.33 | 6.31 | 20.1 |
| IS-02 | Impact | 6.24 | 6.27 | 6.25 | 6.25 | 20.1 |
| IS-03 | Impact | 6.38 | 6.35 | 6.37 | 6.37 | 20.1 |
| CS-01 | Control | 6.82 | 6.80 | 6.83 | 6.82 | 20.1 |
| CS-02 | Control | 6.91 | 6.88 | 6.90 | 6.90 | 20.1 |
| CS-03 | Control | 6.77 | 6.79 | 6.78 | 6.78 | 20.1 |

Impact soils returned mean pH values of 6.25 to 6.37 (grand mean: 6.31), while control soils had mean pH values ranging from 6.78 to 6.90 (grand mean: 6.83). The consistent acidification of impact soils relative to controls is characteristic of prolonged ammonium-based fertilizer input. When ammonium is deposited on or incorporated into soil, nitrifying bacteria oxidise it to nitrite and subsequently to nitrate, releasing hydrogen ions ($H^+$) at each oxidation step and progressively acidifying the soil matrix (Brady & Weil, 2008):

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O$$

Over time, this nitrification-driven acidification can result in a measurable and persistent pH depression in soils exposed to continuous nitrogen deposition, as observed here. The impact soil pH values (range: 6.24–6.38) fall within the slightly acidic range and, while they do not represent severe acidification, the systematic difference from control values (range: 6.77–6.90) is both statistically significant and ecologically meaningful, with implications for nutrient availability, microbial community composition, and the mobility of trace metals in the soil profile (Guo et al., 2010).

### 4.3.3 Soil Electrical Conductivity

Electrical conductivity of soil was determined on 1:5 (w/v) soil-to-deionised water extracts, prepared by shaking 10 g of air-dried soil with 50 mL of deionised water for 30 minutes and then measuring the filtered extract using the Milwaukee Mi 180 in EC mode. Deionised water with a measured EC of 0.55 µS/cm (Plate 4.6) was used as the diluent to minimise background conductivity contributions. The results are presented in Table 4.6.




***Plate 4.6: Quality verification of deionised water used for soil EC extractions. Milwaukee Mi 180 reading of 0.55 µS/cm at 18.7°C (Left) and 0.55 µS/cm at 18.6°C (Right), confirming the ultrapure quality of the diluent and the negligible background conductivity contribution to extract measurements.***

***Table 4.6: Soil Electrical Conductivity of Impact and Control Soil Samples (1:5 Aqueous Extract)***

| Sample ID | Site Type | Rep 1 (mS/cm) | Rep 2 (mS/cm) | Rep 3 (mS/cm) | Mean (mS/cm) |
|---|---|---|---|---|---|
| IS-01 | Impact | 0.284 | 0.287 | 0.285 | 0.285 |
| IS-02 | Impact | 0.291 | 0.289 | 0.293 | 0.291 |
| IS-03 | Impact | 0.278 | 0.281 | 0.280 | 0.280 |

| Sample ID | Site Type | Rep 1 (mS/cm) | Rep 2 (mS/cm) | Rep 3 (mS/cm) | Mean (mS/cm) |
|---|---|---|---|---|---|
| CS-01 | Control | 0.138 | 0.140 | 0.139 | 0.139 |
| CS-02 | Control | 0.132 | 0.130 | 0.133 | 0.132 |
| CS-03 | Control | 0.141 | 0.143 | 0.142 | 0.142 |

*Note: EC values measured in mS/cm. Deionised water blank EC: 0.55 µS/cm (0.00055 mS/cm). Extract measurements were corrected for temperature to 25°C using the Mi 180 ATC function.*

Impact soils exhibited mean EC values of 0.280 to 0.291 mS/cm (grand mean: 0.285 mS/cm), compared to 0.132 to 0.142 mS/cm at control sites (grand mean: 0.138 mS/cm). The dissolved salt load in impact soils was thus approximately twice that of control soils. The quality of the deionised water diluent was verified prior to extract preparation (EC = 0.55 µS/cm; Plate 4.6), confirming that background conductivity contributed negligibly to measured extract values. The elevated EC in impact soils is consistent with the accumulation of soluble fertilizer salts — particularly ammonium nitrate, potassium chloride, and associated ionic species — in the topsoil profile proximal to the blending facility. This corroborates both the total nitrogen and pH data in indicating a fertilizer-derived contamination gradient emanating from the Superfert plant.

### 4.4 General Discussion

Taken together, the results of this study present a coherent and internally consistent picture of environmental nitrogen enrichment in the immediate vicinity of the Superfert Pvt Ltd blending plant. Impact boreholes showed elevated nitrate and — where quantifiable — ammonium nitrogen concentrations, reduced pH, and markedly higher electrical conductivity relative to control boreholes. These patterns were closely mirrored in the soil data, where impact topsoils exhibited substantially higher total nitrogen, lower pH, and elevated EC compared to control soils. The spatial co-occurrence of these changes across multiple parameters, all in a consistent directional pattern that positions impact sites as more chemically altered than control sites, makes a compelling case for the facility as the primary driver of the observed contamination gradient.

The blending of nitrogen-rich fertilizer compounds — principally ammonium nitrate and urea-based products — combined with the inevitable generation of fine dust, potential spillage, and surface drainage from the plant premises, creates multiple overlapping pathways by which reactive nitrogen species can be transferred to the surrounding soil and shallow groundwater. This multi-pathway exposure model is consistent with the conceptual framework established in Chapter Two. The total nitrogen enrichment of impact soils (mean: 312.2 mg/kg versus 148.8 mg/kg in controls)

is the most directly diagnostic finding: it confirms that substantial additional nitrogen has been deposited into or retained within the topsoil profile at impact sites, and provides a soil-based source reservoir from which continued leaching to groundwater can be expected.

The below-detection-limit result for ammonium at sample IW-02 serves as a timely reminder that environmental contamination is rarely spatially uniform. Localised variation in soil texture, organic matter content, groundwater flow paths, and the residence time of water in the vadose zone can all create pockets within an otherwise enriched zone where a given parameter may not be detectable at the sensitivity of the chosen method. This variability does not invalidate the overall finding of nitrogen enrichment at impact sites; rather, it reflects the inherent complexity of field-based environmental monitoring and underscores the value of collecting multiple samples per site category.

With respect to regulatory thresholds, all measured nitrate concentrations (maximum 1.54 mg/L) remain substantially below the WHO guideline of 50 mg/L $NO_3^-$ and the Zimbabwe Standard of 10 mg/L (ZESA, 2014). However, the gradient of enrichment is ecologically meaningful and, if the facility continues to operate without adequate runoff and dust management controls, may present a more serious concern for groundwater quality over time. Long-term monitoring of nitrate and ammonium concentrations, complemented by isotopic analysis ($\delta^{15}N$) to definitively fingerprint the fertilizer-derived nitrogen source and distinguish it from other potential contributors (e.g., septic systems, agricultural application), is recommended as a priority for future investigation.

### 4.5 Chapter Summary

This chapter has presented and discussed the laboratory results for all environmental quality parameters assessed in this study. Statistically significant elevations in nitrate concentration, ammonium nitrogen (in two of three impact samples), water electrical conductivity, soil total nitrogen, and soil electrical conductivity, coupled with significant depressions in both water and soil pH, were consistently observed at impact sites relative to control sites. The independent samples t-test confirmed significant differences ($p < 0.05$) for all seven parameters, supporting rejection of the null hypothesis and acceptance of the alternative hypothesis that the Superfert facility is associated with measurable changes in surrounding soil and water quality. The practical and theoretical implications of these findings, together with recommendations for environmental management and future research, are presented in Chapter Five.

# Chapter Five: Conclusions and Recommendations

## 5.1 Introduction

This chapter synthesises the findings of the study in relation to its stated objectives and hypotheses, draws conclusions about the environmental impact of the Superfert Pvt Ltd fertilizer blending facility on surrounding soil and water quality, and proposes practical recommendations for environmental management, regulatory oversight, and future research. The chapter is structured to move from specific findings to broader implications, and from the local context of Superfert to the wider policy and scientific discourse surrounding industrial nitrogen management in Zimbabwe.

## 5.2 Summary of Key Findings

The central question posed by this study was whether proximity to the Superfert Pvt Ltd fertilizer blending facility in Zimbabwe is associated with measurable changes in soil and water quality. The empirical evidence gathered through this investigation answers this question affirmatively and with statistical certainty. Across all seven environmental quality parameters assessed — water nitrate concentration, water ammonium nitrogen, water pH, water electrical conductivity, soil total nitrogen, soil pH, and soil electrical conductivity — statistically significant differences ($p < 0.05$) were detected between impact sites near the facility and control sites located outside the zone of industrial influence.

Borehole water at impact sites contained nitrate concentrations averaging 1.44 mg/L, compared to 0.66 mg/L at control sites, representing a 2.2-fold elevation. Water ammonium nitrogen at quantifiable impact sites (IW-01 and IW-03) averaged 0.49 mg/L, approximately 3.4 times the control mean of 0.14 mg/L. Water pH was consistently depressed at impact sites (mean: 6.84) relative to controls (mean: 7.13), and electrical conductivity at impact boreholes was substantially higher in two of three samples, reflecting elevated dissolved ion loads attributable to fertilizer-derived solutes. One impact borehole (IW-02) returned a below-detection-limit ammonium result, illustrating the spatial heterogeneity inherent in field-based environmental monitoring, but this outcome did not invalidate the overall pattern of enrichment at impact sites.

The soil data provided the most unambiguous evidence of facility-associated environmental impact. Total nitrogen in impact soils averaged 312.2 mg/kg, more than double the control mean of 148.8 mg/kg. Soil pH at impact sites was consistently lower (grand mean: 6.31) than at control

sites (grand mean: 6.83), consistent with long-term ammonium deposition and subsequent nitrification-driven acidification. Soil electrical conductivity at impact sites (grand mean: 0.285 mS/cm) was approximately twice that at control sites (grand mean: 0.138 mS/cm), corroborating the accumulation of soluble fertilizer salts in the near-surface soil profile.

### 5.3 Conclusions in Relation to Research Objectives

#### 5.3.1 Objective One: Soil Quality Characteristics Near the Superfert Facility

The first objective sought to determine soil quality characteristics at selected distances from the Superfert plant. This objective was fully met. Impact soils showed markedly elevated total nitrogen, reduced pH, and higher electrical conductivity compared to control soils. The spatial pattern of these changes — consistently observed across three independent impact sampling sites — is compatible with a gradient of contamination originating from the blending plant. The source-pathway-receptor model articulated in Chapter Two is supported by these findings: the facility acts as a nitrogen source, and topsoil in the surrounding area functions as a receptor through dust deposition, surface runoff, and direct contact pathways.

#### 5.3.2 Objective Two: Water Quality in Nearby Groundwater Sources

The second objective sought to evaluate water quality in boreholes near the facility. This objective was fully met. Borehole water at impact sites demonstrated elevated nitrate and ammonium nitrogen concentrations, reduced pH, and in most cases higher electrical conductivity relative to controls. Whilst all nitrate concentrations remained below the WHO guideline of 50 mg/L and the Zimbabwe national standard of 10 mg/L, the relative elevation at impact sites is scientifically meaningful. The results confirm that nitrogen-laden leachate originating from the enriched impact soils is reaching the shallow groundwater system, establishing a soil-to-groundwater nitrogen transfer pathway driven by infiltration and vadose zone percolation.

#### 5.3.3 Objective Three: Comparison Between Impact and Control Sites

The third objective sought to compare environmental quality indicators between impact sites and control sites. This objective was met through rigorous inferential statistical analysis. The independent samples t-test confirmed statistically significant differences ($p < 0.05$) for all seven parameters assessed. Normality was verified using the Shapiro-Wilk test, and homogeneity of

variance was confirmed using Levene's test, validating the parametric approach. On the basis of these results, the null hypothesis — that there is no significant difference in soil and water quality indicators between impact and control sites — is decisively rejected. The alternative hypothesis — that there is a significant difference attributable to proximity to the Superfert facility — is accepted.

### 5.4 Contextualisation within the Broader Literature

The findings of this study are broadly consistent with the international and regional literature reviewed in Chapter Two. The direction of all observed changes — elevated nitrogen, depressed pH, elevated conductivity — mirrors what has been reported in studies of nitrogen deposition around industrial facilities and intensive agricultural operations worldwide (Galloway et al., 2008; Guo et al., 2010; Ozlu & Kumar, 2018). Within the Zimbabwean context, the results extend the existing knowledge base beyond field-application studies (Wuta et al., 2016; Mapanda et al., 2012) to encompass an industrial fertilizer handling site, addressing the specific knowledge gap identified in Chapter Two.

Importantly, this study confirms the utility of the source-pathway-receptor model as an interpretive framework for industrial environmental assessment in developing country settings. Distance-based sampling paired with carefully selected control sites proved effective in discriminating facility-associated environmental changes from background variability, validating the methodological approach advocated by Qi et al. (2024) and Lapworth et al. (2017). The use of standard Zimbabwean and internationally recognised analytical procedures (Bremner, 1996; APHA, 2017) ensures comparability of the findings with the wider literature.

### 5.5 Implications for Environmental Management

Despite the fact that current nitrate concentrations in borehole water remain below regulatory thresholds, the study findings carry important implications for environmental management at and around the Superfert facility. The documented nitrogen enrichment of impact soils represents a persistent subsurface nitrogen pool that will continue to contribute to groundwater nitrate loading as long as the driving source — fertilizer dust deposition and surface runoff from the plant — remains unmanaged. Without intervention, continued nitrogen accumulation in the soil profile

could eventually lead to groundwater nitrate concentrations approaching or exceeding regulatory limits, particularly during periods of high rainfall and active leaching.

The following environmental management measures are recommended on the basis of the study findings:

- Dust and Particulate Emission Controls: The facility should implement or enhance engineering controls for dust suppression during blending, bagging, and material transfer operations. These may include enclosed conveying systems, dust extraction and filtration units, and regular wet-suppression protocols in outdoor areas where fertilizer materials are handled.
- Stormwater and Surface Runoff Management: Dedicated drainage channels, perimeter berms, and containment structures should be constructed or upgraded to intercept surface runoff from the plant premises before it can enter the surrounding soil and groundwater system. Runoff collected within the facility boundary should be treated or reused rather than allowed to discharge to the surrounding environment.
- Routine Environmental Monitoring Programme: The facility should establish a formalised groundwater and soil monitoring programme, with quarterly sampling of boreholes at the impact and control locations used in this study. Monitoring data should be reported to the Zimbabwe Environment Management Agency (ZEMA) in accordance with applicable regulations and used to track temporal trends in nitrogen loading around the plant.
- Isotopic Source Fingerprinting: Future monitoring should incorporate nitrogen isotope analysis ($\delta^{15}N$) of borehole water and soil samples to provide definitive attribution of the detected nitrogen to fertilizer sources, distinguishing it from background agricultural and sanitation inputs. This will strengthen the evidentiary basis for any regulatory enforcement or management intervention.
- Buffer Zone Assessment: The spatial extent of the nitrogen enrichment gradient should be characterised more precisely by expanding the sampling network to greater distances from the facility boundary and to more compass directions. This information will allow a defensible buffer zone to be established around the plant, within which land use and water extraction should be subject to enhanced scrutiny.

### 5.6 Implications for Policy and Regulation

At the regulatory level, this study provides empirical evidence that fertilizer blending facilities in Zimbabwe are capable of producing measurable environmental impacts on surrounding soil and water quality, even where current concentrations remain below guideline values. This finding has implications for how such facilities are regulated under the Zimbabwe Environmental Management Act and associated subsidiary legislation.

Environmental Impact Assessments (EIAs) for existing and proposed fertilizer blending and storage facilities should incorporate soil and water quality monitoring as a standard component,

with baseline data collected prior to commencement of operations to enable detection of change over time. Regulatory authorities, particularly ZEMA, should develop or refine sector-specific standards for nitrogen emissions and discharges from fertilizer handling operations, drawing on the methodological and interpretive framework demonstrated in this study. The establishment of facility-specific Environmental Management Plans (EMPs) with binding monitoring and reporting obligations would provide a mechanism for ensuring ongoing accountability and adaptive management.

### 5.7 Limitations of the Study and Directions for Future Research

Several limitations of the current study should be acknowledged as they qualify the conclusions drawn and define the scope for future research. First, the study was conducted during a single sampling campaign and therefore provides a temporal snapshot of environmental conditions rather than a longitudinal record. Seasonal variation in rainfall, temperature, and groundwater recharge can significantly influence nitrogen mobility, and a single sampling event may over- or under-represent the true average condition. Longitudinal monitoring across multiple seasons and years would provide a more robust assessment of the cumulative and dynamic impacts of facility operations.

Second, the number of sampling sites — three impact and three control sites for both soil and water — is relatively small, reflecting the constraints of a single-investigator undergraduate study. A larger sampling design, with a greater number of sites spanning multiple distances and compass directions from the facility, would provide greater statistical power and a more complete spatial characterisation of the contamination gradient.

Third, this study assessed a targeted suite of nitrogen-related parameters and did not examine other potential contaminants associated with fertilizer operations, such as heavy metals (cadmium in phosphate fertilizers), trace organic compounds, or microbiological indicators. A more comprehensive multi-parameter assessment would provide a fuller picture of the environmental footprint of the facility.

Fourth, attribution of the observed changes solely to the Superfert facility is constrained by the presence of other potential nitrogen sources in the surrounding landscape, including residential areas, small-scale agriculture, and on-site sanitation. While the use of control sites and the

consistent directionality of all findings support facility attribution, isotopic confirmation ($\delta^{15}N$) would strengthen causal inference considerably.

Building on these limitations, future research directions of particular relevance include: multi-seasonal monitoring of soil and borehole water at the existing and additional sampling locations; nitrogen isotope analysis ($\delta^{15}N$ and $\delta^{18}O$) for definitive source fingerprinting; assessment of groundwater nitrate concentrations at greater distances from the facility to determine the spatial extent of the contamination plume; and comparison of environmental quality indicators at the Superfert site with those at other fertilizer blending facilities in Zimbabwe and the region to determine whether the findings are site-specific or representative of a wider industrial pattern.

### 5.8 Final Conclusions

This study set out to evaluate whether the Superfert Pvt Ltd nitrogen-based fertilizer blending facility in Zimbabwe is associated with measurable environmental changes in surrounding soil and water quality. The investigation produced clear, statistically robust evidence that it is. All seven environmental quality parameters examined — water nitrate, water ammonium nitrogen, water pH, water electrical conductivity, soil total nitrogen, soil pH, and soil electrical conductivity — differed significantly ($p < 0.05$) between impact sites in the vicinity of the plant and control sites located outside the zone of industrial influence, leading to unambiguous rejection of the null hypothesis.

The magnitude of the differences observed — with impact soils containing more than twice the total nitrogen of control soils and impact groundwater showing 2.2-fold elevated nitrate concentrations — is consistent with an active and ongoing nitrogen transfer from the facility to the surrounding environment, mediated by dust deposition, surface runoff, and vadose zone leaching. While current water quality values remain within regulatory limits, the soil nitrogen reservoir documented at impact sites represents a latent risk for future groundwater nitrate enrichment if facility-level emission and runoff controls are not strengthened.

This study contributes to a growing but still limited body of evidence on the environmental consequences of industrial fertilizer handling in sub-Saharan Africa. It demonstrates that even blending-level operations — not just manufacturing — can produce detectable and ecologically meaningful impacts on local soil and water quality. It further demonstrates that rigorous environmental assessment, based on standard analytical methods, appropriate statistical analysis,

and well-designed control site comparison, can generate actionable evidence to support improved environmental governance of such facilities.

In a broader context, the findings underscore the importance of integrating environmental monitoring into the operational frameworks of fertilizer industries across Zimbabwe and similar developing economies, where the intersection of growing food security imperatives, expanding fertilizer use, and limited environmental oversight creates conditions in which undetected industrial environmental impacts can accumulate over time. Proactive, evidence-based environmental stewardship — of the kind this study was designed to promote — is therefore not merely an academic exercise but a practical necessity for sustainable industrial development.

### 5.9 Chapter Summary

This chapter has synthesised the findings of the study, drawn conclusions in relation to each research objective, and contextualised the results within the broader scientific and regulatory literature. The null hypothesis was rejected on the basis of statistically significant differences ($p < 0.05$) across all seven parameters, confirming an association between the Superfert facility and measurable environmental changes in surrounding soil and water quality. Practical recommendations for environmental management were provided, covering dust control, stormwater management, routine monitoring, isotopic source fingerprinting, and buffer zone assessment. Limitations of the study were acknowledged and a programme of future research was outlined. The study concludes that the Superfert Pvt Ltd fertilizer blending facility is associated with a detectable and ecologically meaningful nitrogen contamination gradient in its vicinity, and that strengthened environmental management measures are warranted to prevent deterioration of local soil and water resources over time.

## References


Adimalla, N., & Qian, H. (2019). Groundwater quality evaluation using water quality index (WQI) for drinking purposes and human health risk (HHR) assessment in an agricultural region of Nanganur, south India. Ecotoxicology and Environmental Safety, 176, 153–161.

American Public Health Association (APHA). (2017). Standard methods for the examination of water and wastewater (23rd ed.). APHA, AWWA, WEF.

Anas, M., Liao, F., Verma, K. K., Sarwar, M. A., Mahmood, A., Chen, Z. L., Li, Q., Zeng, X. P., Liu, Y., & Li, Y. R. (2020). Fate of nitrogen in agriculture and environment: Agronomic, eco-physiological and molecular approaches to improve nitrogen use efficiency. Biological Research, 53(1), 47.

Bijay-Singh, & Craswell, E. (2021). Fertilizers and nitrate pollution of surface and ground water: An increasingly pervasive global problem. SN Applied Sciences, 3(4), 518.

Brady, N. C., & Weil, R. R. (2008). The nature and properties of soils (14th ed.). Prentice Hall.

Bremner, J. M. (1996). Nitrogen—total. In D. L. Sparks (Ed.), Methods of soil analysis: Part 3 chemical methods (pp. 1085–1121). Soil Science Society of America.

Bryman, A. (2016). Social research methods (5th ed.). Oxford University Press.

Galloway, J. N., Townsend, A. R., Erisman, J. W., Bekunda, M., Cai, Z., Freney, J. R., Martinelli, L. A., Seitzinger, S. P., & Sutton, M. A. (2008). Transformation of the nitrogen cycle: Recent trends, questions, and potential solutions. Science, 320(5878), 889–892.

Guo, J. H., Liu, X. J., Zhang, Y., Shen, J. L., Han, W. X., Zhang, W. F., Christie, P., Goulding, K. W. T., Vitousek, P. M., & Zhang, F. S. (2010). Significant acidification in major Chinese croplands. Science, 327(5968), 1008–1010.

Helsel, D. R. (2012). Statistics for censored environmental data using Minitab and R (2nd ed.). Wiley.

Lapworth, D. J., Nkhuwa, D. C. W., Okotto-Okotto, J., Pedley, S., Stuart, M. E., Tijani, M. N., & Wright, J. (2017). Urban groundwater quality in sub-Saharan Africa: Current status and implications for water security and public health. Hydrogeology Journal, 25(4), 1093–1116.

Makaya, E. (2023). Spatial analysis of groundwater quality in Bulawayo, Zimbabwe. Journal of African Earth Sciences.

Mapanda, F., Wuta, M., Nyamangara, J., & Rees, R. M. (2012). Nitrogen leaching and indirect nitrous oxide emissions from fertilized croplands in Zimbabwe. Nutrient Cycling in Agroecosystems, 94(1), 85–96.

Martínez-Dalmau, J., Berbel, J., & Ordóñez-Fernández, R. (2021). Nitrogen fertilization: A review of the risks associated with the inefficiency of its use and policy responses. Sustainability, 13(10), 5625.

Moloanto, K. M., Khasipe, T. S., & Cason, E. D. (2022). Nitrate water contamination from industrial activities and complete denitrification as a remediation option. Water, 14(5), 799.

Nyamangara, J., Bergström, L. F., Piha, M. I., & Giller, K. E. (2003). Fertilizer use efficiency and nitrate leaching in a tropical sandy soil. Journal of Environmental Quality, 32(2), 599–606.

Odiyo, J. O., Mathoma, J., & Makungo, R. (2018). Chemical and microbial quality of groundwater in rural settlements. International Journal of Environmental Research and Public Health, 15(2), 317.

Ozlu, E., & Kumar, S. (2018). Response of soil organic carbon, pH, electrical conductivity, and water stable aggregates to long-term annual manure and inorganic fertilizer. Soil Science Society of America Journal, 82(5), 1243–1251.

Qi, J., Lu, X., Sai, N., Liu, Y., & Du, W. (2024). Heavy metal concentrations in soil and ecological risk assessment in the vicinity of Tianzhu Industrial Park, Qinghai-Tibet Plateau. PeerJ, 12, e18510.

Rayment, G. E., & Lyons, D. J. (2011). Soil chemical methods—Australasia. CSIRO Publishing.

Rivett, M. O., Buss, S. R., Morgan, P., Smith, J. W. N., & Bemment, C. D. (2008). Nitrate attenuation in groundwater: A review of biogeochemical controlling processes. Water Research, 42(16), 4215–4232.

Royston, P. (1992). Approximating the Shapiro-Wilk W-test for non-normality. Statistics and Computing, 2, 117–119.

Tongco, M. D. C. (2007). Purposive sampling as a tool for informant selection. Ethnobotany Research and Applications, 5, 147–158.

Ward, M. H., Jones, R. R., Brender, J. D., de Kok, T. M., Weyer, P. J., Nolan, B. T., Villanueva, C. M., & van Breda, S. G. (2018). Drinking water nitrate and human health: An updated review. International Journal of Environmental Research and Public Health, 15(7), 1557.

World Health Organization (WHO). (2017). Guidelines for drinking-water quality (4th ed., incorporating 1st addendum). WHO.

Wuta, M., Nyamadzawo, G., Mlambo, J., Nyamugafata, P., Tauro, T., Nyamangara, J., & Rees, R. M. (2016). Ground and surface water quality along a dambo transect in Chihota smallholder farming area, Marondera district, Zimbabwe. Physics and Chemistry of the Earth, Parts A/B/C, 92, 35–42.

Yin, R. K. (2018). Case study research and applications: Design and methods (6th ed.). SAGE Publications.

Zimbabwe Environment Management Agency (ZEMA). (2014). Standards for water and wastewater. Government Printer.