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83rd INAUGURAL LECTURE

SECURING THE PRODUCER: CROP NUTRITION AND FOOD SECURITY

by

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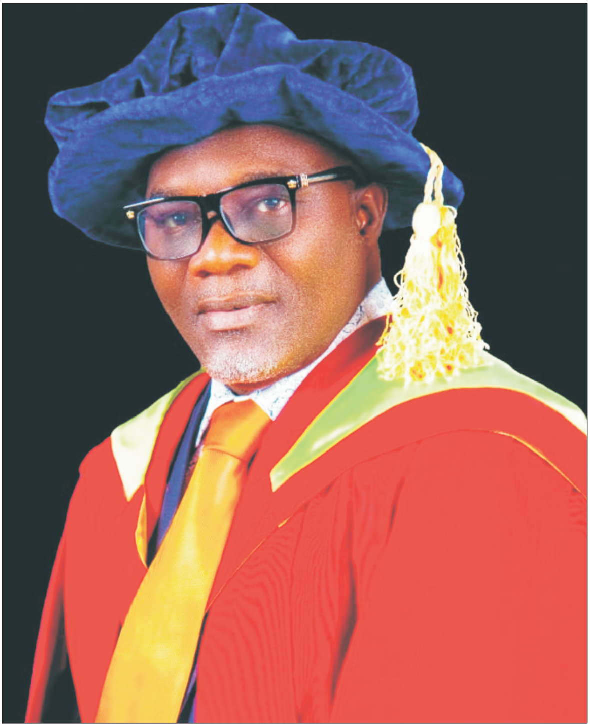

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SECURING THE PRODUCER: CROP NUTRITION AND FOOD SECURITY

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Members of my immediate and extended families,
Distinguished Fellows and Members of the Agricultural Society of Nigeria,
Gentlemen of the press,
Distinguished Ladies and gentlemen,
Great FUNAABITES!

1.0 PROEM

With profound humility and heartfelt gratitude to Almighty God, I stand before you today to deliver an Inaugural Lecture entitled "Securing the producer: Crop Nutrition and Food Security." This momentous occasion has been made possible by the esteemed tradition of our University which recognizes the importance of showcasing the academic pursuits of its Professors on for a such as this. I extend my deepest appreciation to the Vice Chancellor and Chairman of the Senate, Prof. Olusola Babatunde Kehinde for granting me the privilege to present this lecture which is the 4th in the Department of Crop Production and Plant Physiology, 17th in the College of Plant Science and Crop Production, and 83rd in the Federal University of Agriculture, Abeokuta.

As I embark on this scholarly journey, I am perspicaciously aware of the responsibility entrusted to me, and I approach this task with utmost dedication and reverence. It is my most sincere hope that this Inaugural Lecture will serve as a platform to illuminate the intricate pathways that lead us from the soil beneath our feet to the nourishing bounty of the sumptuous meals that graces our tables.

Together, let us take a trip into the captivating world of crop nutrition and production, where the near-extremes of human creativity, cutting-edge research and innovative strategies converge to unlock the full potential of our agricultural practices. Through a comprehensive exploration of soil dynamics, nutrient management, sustainable and innovative cultivation techniques, we endeavored to pave the way for enhanced crop nutrition in order to contribute to the noble pursuit of global food security.

May this Inaugural Lecture ignite the flames of curiosity, inspire collaborative endeavors, and stimulate a passion for transformative change in the realm of crop nutrition.

2.0 INTRODUCTION

Farming is an ancient practice that is deeply woven into the fabric of human existence. It is an endeavour that relies on the delicate interplay between plants and their environment, particularly the sun and the soil. Unlike humans, plants depend primarily on these specific sources of nourishment to thrive. What sets plants apart as remarkable autotrophs is their extraordinary ability to harness the energy of the sun, combine with carbon dioxide and water to create their own food. Within the intricate domain of their chlorophyll-filled leaves, plants perform the wondrous task of converting simple sugars into complex compounds, thereby fueling the growth and vitality of their various plant parts. For instance, cassava (*Manihot esculentus*), a root crop, exemplifies the mastery of starch production through this incredible process. Furthermore, this wondrous capacity of plants to trap the ingredients of nature is seen in the very origin of plant life. Seeds are the embodiment of the future hope and potentials in life. When a seed germinates, it absorbs water, embarking on a journey of respiration and transformation. Through enzymatic action, the cotyledon or endosperm disintegrates, providing nourishment for the developing embryo. The radicle emerges, giving birth to the roots, while the plumule takes shape, eventually blossoming into the magnificent shoot adorned with stems, branches, leaves, flowers and fruits.

This Inaugural Lecture revolves around the mesmerizing world beneath our feet, from the perspective of a Crop Nutritionist. Crop nutrition is an essential aspect of agriculture that encompasses the study of nutrient requirements, uptake, assimilation, and utilization by plants. It involves understanding the interactions between plants and their environment, including the soil, water, and atmosphere.

Nutrients are chemical elements required by plants for their biochemical processes, and they can be broadly categorized as macronutrients and micronutrients (Marschner, 2012). Macronutrients, such as nitrogen (N), phosphorus (P), and potassium (K) are needed in relatively large quantities, while micronutrients, such as iron (Fe), zinc (Zn), and manganese (Mn) are required in smaller amounts. According to Fagaria (2011), a balanced supply of these nutrients is essential for plants to carry out vital functions such as photosynthesis, respiration, nutrient absorption, hormone synthesis, and defense against pests and diseases. In their quest for survival and prosperity, plant roots embark on a relentless exploration of the soil, diligently searching for those crucial mineral nutrients. While the early stages of plant development rely on the sustenance provided by the mother seed via the cotyledon as seedlings mature, the plant becomes dependent on the soil's nutrient reservoirs and the sun's radiant energy. Hence, it is important to emphasize that this unique plant's ability to harness the sun's power for its autotrophic activities hinges on the availability of these essential nutrients in the soil.

Indeed, the soil is a reservoir of a precious commodity. Over time, this invaluable resource becomes depleted, necessitating its replenishment to ensure an uninterrupted support of life. Similarly, plants require to have access to these nutrients in order to sustain their growth and fulfill their primary role of alimentation of man. However, the overexploitation of soil resources and the excessive use of chemical fertilizers have resulted in a disruption in the supply of nutrients. Shockingly, more than 40% of fertilizers are lost to erosion, volatilization, and leaching, leading to the release of harmful greenhouse gases into our atmosphere and the contamination of precious underground water sources (Oenema *et al.* 2019). Our soils have become acidic, leading to a surge in pest and disease incidence (Simon *et al* 2016), while also raising concerns about the adverse effects on human health. The consequences of human activities, climate change and global warming, have given rise to unpredictable weather patterns, marked by erratic water availability—either being excessive or

insufficient. One of the primary contributors to these challenges is the excessive use of chemicals in our farming practices.
Crop nutrition is a dynamic and multifaceted field that profoundly influences crop growth, yield, and nutritional quality. It forms the bedrock of cultivating healthy, productive crops that sustain global food systems. With a growing population and increasing demands for food security, it is vital to explore innovative strategies that enhance crop nutrition. The journey of a crop, from seed to table, encompasses a complex interplay of soil health, nutrient availability, plant physiology, and human nutrition. Understanding the intricacies of crop nutrition is essential for tackling the challenges of food security, environmental sustainability, and human health in a rapidly expanding world population. Furthermore, it elicits the concept of pay-back (reciprocity) wherein the plant, which is main source of food for man, is not neglected. This Inaugural Lecture offers a glimpse into the captivating realm of crop nutrition and food security, as well as my stewardship as a Crop Nutritionist.

2.1 Challenges in Plant Nutrition

Challenges in plant nutrition have global implications, and Nigeria is no exception to these pressing issues. Farmers worldwide face hurdles such as yield loss, underground water contamination, runoff, limited nutrient sources, escalating fertilizer costs, and suboptimal fertilizer usage. These challenges are particularly crucial to address as we strive to feed Nigeria's rapidly growing population.

In terms of yield loss, farmers globally struggle with inadequate plant nutrition, leading to diminished crop yields. Nutrient deficiencies, such as nitrogen, phosphorus, and potassium, can significantly hinder plant growth and development, resulting in suboptimal harvests. This yield gap not only affects individual farmers but also impacts the overall agricultural productivity of nations. The contamination of underground water sources is a pervasive issue across the globe. Improper use and management of fertilizers contribute to the leaching of nutrients into the soil, which eventually find their way into water bodies. This contamination poses environmental risks and threatens both human health and ecosystems that rely on these water sources. Runoff, especially in regions with heavy rainfall, presents a significant challenge. Inappropriate application practices or excessive use of fertilizers can lead to nutrient-rich runoffs. This runoff erode valuable nutrients away from the fields and pollutes nearby water bodies. The ecological imbalances caused by nutrient runoff exacerbate water contamination issues and further degrade agricultural lands. The availability of diverse and affordable nutrient sources is crucial for sustainable agriculture on a global scale. Farmers worldwide face challenges in accessing quality fertilizers and other nutrient sources necessary for optimal plant nutrition. This limited availability impedes their ability to nourish crops effectively and thus hindering agricultural productivity. Escalating fertilizer costs pose a common burden for farmers around the world. Rising prices, coupled with limited financial resources, restrict farmers' capacity to acquire and apply fertilizers adequately. Consequently, farmers resort to reduced fertilizer usage, resulting in compromised plant nutrition and reduced yields.

While these challenges have global ramifications, their impact is particularly pronounced in Nigeria. As the country's population continues to grow at a rapid pace, ensuring food security becomes an urgent national priority. Insufficient yields, water contamination, limited nutrient sources, and escalating fertilizer costs directly threaten Nigeria's ability to meet the nutritional needs of its citizens. Food scarcity, malnutrition, and an unstable food security landscape loom as potential consequences. Addressing these challenges in plant nutrition requires collaborative efforts between researchers, policymakers, and agricultural stakeholders. Sustainable farming practices, research and innovation, improved access to diverse and affordable nutrient sources, and proper fertilizer application techniques are vital for overcoming these obstacles. By taking proactive measures, Nigeria can secure a more prosperous and food-secure future, ensuring that its growing population is adequately nourished and thriving.

2.2 Soil Health and Nutrient Management

Soil health refers to the capacity of soil to function as a vital living system within the ecosystem and land-use boundaries, to sustain biological productivity, maintain environmental quality, and promote plant, animal, and human health (Doran and Zeiss, 1996). Soil health is a crucial aspect of crop nutrition as it directly influences the availability and accessibility of nutrients to plants (Singh *et al.* 2017). Soil serves as the primary medium for nutrient storage, transformation, and uptake by plants. However, soil health and nutrient availability are often compromised due to various factors, including intensive agricultural practices, erosion, nutrient depletion, and pollution. Unfortunately, modern agricultural practices such as intensive monocropping, excessive tillage, and over-reliance on chemical inputs have contributed to the degradation of soil health in many regions. This degradation leads to nutrient imbalances, reduced nutrient availability, and increased susceptibility to erosion and pollution. Thus, sustainable soil management practices are essential for maintaining soil fertility, optimizing nutrient cycling, and minimizing environmental impacts.

To address these challenges and promote sustainable crop nutrition, it is essential to implement soil management practices that prioritize soil health and nutrient cycling (Lal, 2015). Sustainable soil management practices aim at improving soil structure, organic matter content, microbial activity, and nutrient retention capacity. By enhancing these soil properties, farmers can ensure optimal nutrient availability for crops while minimizing nutrient losses and environmental impacts.

One of the key components of sustainable soil management is the incorporation of organic matter into the soil. Organic matter, derived from plant residues, animal manure, compost, or cover crops, serves as a valuable source of nutrients and helps improve soil structure. It enhances water-holding capacity, promotes soil aeration, and provides a favorable environment for beneficial soil microorganisms. Additionally, organic matter acts as a reservoir for nutrients, releasing them slowly over time, and reducing the risk of nutrient leaching or runoff. Organic farming emphasizes the use of natural fertilizers, compost, cover crops, and crop rotation to enhance soil health and nutrient availability while minimizing the use of synthetic chemicals. Conservation agriculture, with its focus on minimum soil disturbance, soil cover, and diversified cropping systems also aims at improving soil structure, moisture retention, and nutrient cycling.

Crop rotation and diversification are also essential practices for maintaining soil health and nutrient management. Crop rotation is the practice of growing different crops in succession on the same land, with the intention of improving or maintaining soil fertility, controlling insect pests, diseases, and weeds, and eventually optimizing crop yields (Hatfield *et al.* 2020). Rotating crops with different nutrient requirements help prevent nutrient depletion and reduces the build-up of pests and diseases (Weston and Ryan 2018). Additionally, incorporating cover crops, such as legumes or grasses into the rotation, can fix atmospheric nitrogen, improve soil structure, and scavenge residual nutrients, thereby reducing the need for synthetic fertilizers.

Soil conservation practices such as conservation tillage, crop rotation, contour ploughing and cover crops are critical for preventing soil erosion which can lead to the loss of valuable topsoil and nutrients. Techniques such as contour ploughing, terracing, and conservation tillage help minimize soil disturbance, improve water infiltration, and reduce erosion rates. By preserving the integrity of the soil, these practices maintain nutrient-rich topsoil and promote sustainable crop production. To enhance soil health and nutrient management, it is also important to promote practices that minimize nutrient pollution and protect water resources. Nutrient management strategies consider factors such as nutrient timing, placement, and dosage to prevent excessive nutrient application which can contribute to water pollution through runoff or leaching. Implementing best management practices, such as buffer strips, vegetative filter strips, or controlled drainage systems can help mitigate nutrient losses and protect water quality.

2.3 Nutrient Requirements and Plant Physiology

Understanding the specific nutrient requirements of different crops and their physiological processes is crucial for maximizing crop production and nutrition. Each crop has unique nutrient demands that must be met to support their growth, development, and productivity. Nutrient requirements are influenced by various factors, such as the crop species, growth stage, environmental conditions, and yield goals. Macro and micronutrients play essential roles in different physiological processes of plants. Understanding the availability and accessibility of nutrients in the soil is essential for effective nutrient management. Soil properties, including pH, organic matter content, cation exchange capacity, and nutrient retention capacity, influence nutrient availability to plants. For example, certain nutrients, like iron or phosphorus, may become less available under alkaline soil conditions, while acidic soils may limit the availability of micronutrients like zinc or manganese (Marschner, 2012; Barker *et al.* 2015).

Root architecture and physiology play a vital role in nutrient uptake by plants. Plant roots actively explore the soil, seeking out nutrients through a combination of mechanisms, including root branching, elongation, and the release of organic acids and enzymes. The root system's efficiency in nutrient acquisition is influenced by factors such as root density, root hairs, mycorrhizal associations, and the presence of nodules in leguminous crops. Once absorbed, nutrients are translocated within the plant through the vascular (xylem and phloem) systems. Xylem transports water and dissolved minerals from the roots to the shoots, while phloem distributes organic compounds and nutrients to different plant parts (Taiz *et al.* 2018). These transportation mechanisms ensure the efficient distribution of nutrients to various organs, such as leaves, stems, flowers, and fruits, supporting their growth and development (Chaffey, 2020).

Plant physiology, the study of plant functions and processes, provides insights into the mechanisms of nutrient absorption, translocation, and utilization. Nutrients are incorporated into plant tissues through various metabolic processes like photosynthesis, respiration, and enzyme reactions. Chlorophyll synthesis, for example, requires magnesium (Mg), while nitrogen is crucial for protein synthesis and phosphorus for energy transfer processes within the plant.

Nutrient deficiencies or toxicities can have significant impacts on plant growth and yield. Deficiencies occur when plants do not receive adequate amounts of specific nutrients, leading to visible symptoms and impaired physiological processes. These symptoms may include chlorosis (yellowing) of leaves, stunted growth, poor flowering, or reduced fruit development. Toxicities, on the other hand, occur when nutrient levels surpass the plant's tolerance level, resulting in toxicity symptoms, such as leaf burning, tissue necrosis, or reduced root growth. Recognizing nutrient deficiencies or toxicities through visual symptoms, plant tissue analysis or soil testing is crucial for implementing timely corrective measures. These measures may involve applying fertilizers, soil amendments, or foliar sprays to correct nutrient imbalances and ensure optimal plant nutrition. Precision nutrient management techniques, such as variable rate application or site-specific nutrient management, can be employed to deliver the right amount of nutrients at the right time and location within the field, improving nutrient use efficiency and reducing environmental impacts.

By considering factors such as soil properties, root physiology, and plant metabolic processes, farmers can develop targeted nutrient management strategies that maximize crop productivity, minimize nutrient losses, and support sustainable agricultural practices. The essential nutrients in crops and their deficiency symptoms are presented in Table 1.

Table 1: Essential Nutrients in Crops and their Deficiency Symptoms

Nutrient	Category	Function	Deficiency Symptoms
Nitrogen	Macro	Essential for growth, protein synthesis	Stunted growth, yellowing leaves, reduced yield
Phosphorus	Macro	Energy transfer, root development	Poor root development, dark green leaves, delayed flowering
Potassium	Macro	Enzyme activation, water regulation	Weak stems, leaf margins browning, reduced disease resistance
Calcium	Macro	Cell wall structure, nutrient uptake	Blossom end rot, leaf curling, stunted root growth
Magnesium	Macro	Chlorophyll synthesis, photosynthesis	Yellowing between veins, leaf curling, impaired photosynthesis
Sulfur	Macro	Protein synthesis, enzyme function	Pale leaf color, slow growth, reduced seed production
Iron	Micro	Chlorophyll synthesis, electron transfer	Yellowing of leaves (chlorosis), leaf necrosis
Manganese	Micro	Enzyme activation, photosynthesis	Interveinal chlorosis, stunted growth
Zinc	Micro	Enzyme cofactor, hormone synthesis	Reduced leaf size, interveinal chlorosis
Copper	Micro	Enzyme cofactor, lignin synthesis	Leaf wilting, distorted growth
Boron	Micro	Cell wall synthesis, carbohydrate transport	Brittle leaves, stunted root growth
Molybdenum	Micro	Nitrogen fixation, enzyme function	Yellowing of leaves, stunted growth
Chlorine	Micro	Water movement, osmotic regulation	Wilting, leaf tip necrosis
Nickel	Micro	Enzyme cofactor, nitrogen metabolism	Reduced growth, interveinal chlorosis
Cobalt	Micro	Component of vitamin B12, nitrogen fixation	Reduced growth, delayed maturity
Silicon	Micro	Structural component, stress tolerance	Weaker stems, increased susceptibility to pathogens

Source: Marschner (2012)

3.0 HOW DO PLANTS FEED THEMSELVES?

Plants, like skilled alchemists, possess the remarkable ability to manufacture their own food through a process known as photosynthesis. Harnessing the radiant energy of the sun, plants transform carbon dioxide and water into the life-sustaining elixir of carbohydrates. However, this enchanting dance of photosynthesis is only the beginning, for plants require a diverse array of essential nutrients to thrive and flourish. Just as human beings rely on a balanced diet to meet nutritional needs, plants too have their own menu of essential nutrients.

How do plants acquire these nutrients? The answer lies beneath the surface, where an intricate network of roots extends its delicate tendrils into the soil, embarking on a quest for sustenance. The roots explore the soil, seeking out pockets of nutrients like treasure hunters on a mission. They dance with the soil particles, forming symbiotic relationships with beneficial microorganisms, such as mycorrhizal fungi, which serve as invaluable allies in the quest for nutrient acquisition. As the roots encounter nutrient-rich patches in the soil, they employ a captivating array of strategies to secure their vital sustenance. Some nutrients, like nitrogen, are absorbed in the form of nitrates or ammonium ions, while others, like phosphorus and potassium, are absorbed as ions. The roots, with their microscopic nutrient-seeking hairs, engage in a delicate exchange, drawing in the precious elements that fuel their growth and development.

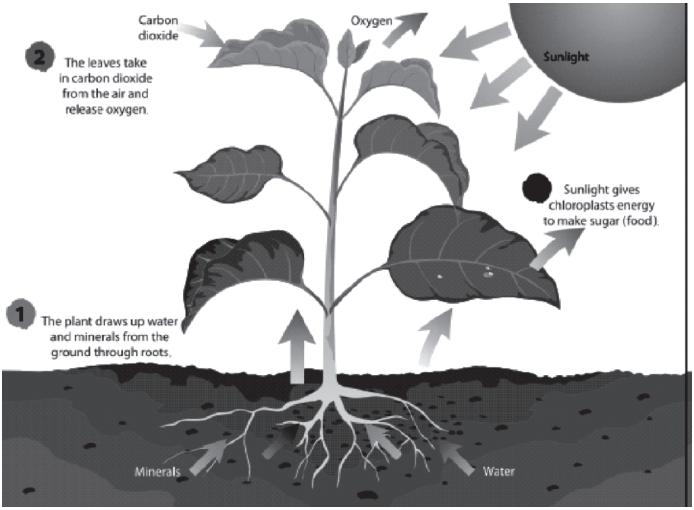

Figure 1: Food production in plant

However, the journey of these nutrients does not end at the root's doorstep. Once inside the plant, an intricate transport system - akin to nature's own highway - guides these nutrients to their designated destinations. Some nutrients ascend through the xylem, reaching the leaves and stems, fueling photosynthesis and growth. Yet, as in any intricate dance, harmony must be maintained. The availability and balance of nutrients play a crucial role in ensuring the plant's vitality. Imbalances can lead to visible symptoms - yellowing leaves, stunted growth, and diminished yield. In these moments, the plant communicates its needs, and it is the responsibility of man as stewards of the green kingdom to listen and respond. In reference to the 71st Inaugural Lecture delivered by Prof O. A. Enikuomehin where he referred to plants as *inaudibles*, they are actually audible to some of plant nutritionists through various signs and symptoms and we respond to their needs appropriately.

It is therefore important to embrace the hidden world of crop nutrition, where the roots reach deep into the recess of mother earth, where nutrients are absorbed, transported, and orchestrated to fuel the growth and vitality of every living plant. In understanding how plants feed themselves, the knowledge to nurture them and optimize their nutrition becomes necessary to forge a future where agriculture and nature walk hand in hand, nourishing the earth and its inhabitants.

3.1 Mechanisms of Plant Nutrition

As we unravel the intricacies of plant nutrition, we gain a profound appreciation for the diverse mechanisms that plants have evolved to nourish themselves. From the root exploration in search of vital nutrients, to the establishment of symbiotic partnerships with microorganisms, plants demonstrate a captivating dance of survival and adaptation. Through their incredible journey of nutrient uptake and transport, they exemplify the interconnectedness of life on earth.

3.1.1 Root Exploration: The Quest for Nutrients

At the heart of plant nutrition lies the intricate network of roots, tirelessly exploring the soil in search of nutrients. Like intrepid adventurers, the roots extend their delicate tendrils, navigating through the intricate matrix of soil particles. They employ various strategies to optimize nutrient acquisition, such as branching, root hairs, and mycorrhizal associations. Root branching allows plants to cover a larger soil volume, increasing their chances of encountering nutrient-rich patches. The fine root hairs, resembling microscopic extensions, dramatically amplify the surface area of the roots, enhancing nutrient absorption. These root hairs ramify around the soil particles, exchanging ions and absorbing nutrients as they intertwine.

3.1.2 Symbiotic Relationships: Allies in Nutrient Acquisition

Plants have forged fascinating partnerships with beneficial microorganisms to enhance nutrient acquisition. One of the most remarkable alliances is formed with mycorrhizal fungi. These extraordinary fungi establish a symbiotic relationship with plant roots, extending their fine filaments, known as hyphae, into the soil. In return, the fungi receive carbohydrates from the plant, while aiding in nutrient uptake.

Mycorrhizal associations offer several advantages. The fungal hyphae act as extensions of the plant's root system, exploring a larger soil volume and accessing nutrients that might be otherwise unavailable to the plant. They also enhance the plant's ability to absorb phosphorus, an essential nutrient that often presents challenges in low-phosphorus soils. This symbiotic dance between plants and mycorrhizal fungi exemplifies the remarkable interdependence and cooperation that exists within the natural world.

3.1.3 Nutrient Uptake and Transport: Nature's Intricate Highways

Once nutrients are encountered by the roots, a fascinating journey commences within the plant. Nutrient uptake occurs through specialized transporters present on the root surface, allowing the selective absorption of specific ions. These ions then travel through the plant's vascular system, primarily composed of xylem and phloem. The xylem serves as nature's hydraulic elevator, transporting water and dissolved minerals from the roots to the leaves and stems. It provides the necessary building blocks for photosynthesis, supporting the plant's growth and metabolic processes. The phloem, on the other hand, acts as a nutrient superhighway, facilitating the movement of sugars, amino acids, and other organic compounds throughout the plant. This enables the distribution of nutrients to all parts of the plant, ensuring a harmonious supply for growth, reproduction, and defense.

3.1.4 Nutrient Sensing and Adaptation: Plant Intelligence at Work

Plants possess an astonishing ability to sense and respond to changes in nutrient availability. They exhibit remarkable adaptive mechanisms to cope with nutrient deficiencies or imbalances.

Through sophisticated signaling pathways, plants can adjust their root architecture, modify nutrient uptake rates, and allocate resources strategically. For example, in response to low-nutrient conditions, plants may develop longer roots, enabling them to explore a larger soil volume. They can also release specific chemical signals called root exudates such as flavonoids, organic acids, sugars, amino acids and peptides that attract beneficial microorganisms, further enhancing nutrient acquisition. Such adaptive responses showcase the intelligence of plants, as they navigate their environment to optimize nutrient uptake and maximize their chances of survival.

4.0 The Interplay of Nutrition: Unveiling the Connection Between Plant and Human Nutrition

It is very important to know that crop nutrition has profound impacts on human well-being. How the remarkable processes of plant nutrition shape the nutritional landscape and influence our health and vitality are as follows:

4.1.1 Plants as Nutritional Powerhouses

Plants serve as the foundation of our food system, providing man with a diverse array of nutrients essential for optimal health. They are nature's nutritional powerhouses, synthesizing a wide range of vitamins, minerals, antioxidants, and phytochemicals. These bioactive compounds not only contribute to the vibrant colors, flavors, and aromas of plants but also hold tremendous potential in promoting human health and disease prevention. From the vitamin C in citrus fruits to the beta-carotene in carrots, plants offer an abundance of micronutrients that play vital roles in supporting our immune system, promoting healthy vision, and protecting against oxidative stress. Moreover, plant-based foods are rich in dietary fiber which aids digestion, regulates blood sugar levels, and supports heart health (Rodríguez-Casado, 2016).

4.1.2 Closing the Loop: Sustainable Food Systems and Plant Nutrition

The exploration of plant nutrition reminds one of the integral roles it plays in building sustainable food systems. By implementing regenerative agricultural practices, such as organic farming, agroforestry, and crop rotation, we can enhance soil health, promote biodiversity, and minimize the reliance on synthetic fertilizers and pesticides.

Innovative approaches like agroecology and permaculture empower to mimic the resilience and efficiency of natural ecosystems, harmonizing plant nutrition with environmental stewardship. These sustainable practices can create a harmonious relationship between plant nutrition, ecological well-being, and the nourishment of both humans and the planet.

5.0 INNOVATIONS IN CROP NUTRITION

Advancements in science and technology have sparked a wave of innovation in the field of crop nutrition, revolutionizing the approach to nutrient management and opening up new possibilities for enhancing crop productivity and nutritional value. These innovations are driven by the pressing need to address challenges such as nutrient loss, environmental impact, and resource constraints while ensuring food security for a growing global population.

5.1 Potential of Nanotechnology in Crop Nutrition

One of the exciting areas of innovation in crop nutrition is the use of ***nanotechnology***. Nanotechnology is a field that focuses on manipulating and controlling matter at the nanoscale, exploiting the unique properties and phenomena that occur at this scale. It involves the design, synthesis, and application of materials, devices, and systems with functional properties at the nanoscale. This multidisciplinary field aims at developing new materials, technologies and applications across various sectors, including medicine, electronics, energy, agriculture, and environmental science. Nanotechnology offers opportunities for innovation and advancement by working with materials at the atomic and molecular levels. The world of crop nutrition is experiencing a revolutionary leap with the integration of nanotechnology. Imagine harnessing the power of the minuscule, where materials are manipulated at the scale of a billionth of a meter. The realm of nanotechnology in crop nutrition is a frontier that promises precise control over nutrient delivery systems and a quantum leap in agricultural efficiency. Nanotechnology offers a palette of possibilities in enhancing crop nutrition by revolutionizing how we deliver nutrients to plants. Through the use of nanomaterials, nutrients can be encapsulated in nanosized particles, acting as tiny nutrient carriers. These nanofertilizers are like superheroes in disguise, stealthily delivering nutrients right to the roots of plants. This targeted and controlled release ensures that plants receive the right nutrients at the right time, maximizing nutrient uptake efficiency. Nanomaterials can be designed to deliver nutrients in a targeted and controlled manner, improving their availability to plants, and reducing nutrient losses (Liu *et al.* 2019).

Nanofertilizers also act as guardians of nutrients, preventing them from escaping into the environment. They form a protective shield around the nutrients, reducing losses through leaching or volatilization. No more watching valuable nutrients wash away with rainfall or dissipate into thin air. Nanotechnology steps in, safeguarding our precious resources and minimizing the environmental impact of nutrient application. The magic of nanotechnology does not end there. Nanosensors, the microscopic guardians of nutrient levels, come into play. These tiny sentinels monitor nutrient concentrations in real-time, providing instant feedback on the nutritional status of plants (Ali *et al.* 2020; Li *et al.* 2021). With this wealth of information at our fingertips, farmers can make informed decisions about nutrient management. Nanosensors bring precision to the field, empowering farmers with the knowledge they need to optimize nutrient application and maximize crop yields.

The use of carbon nanotubes has demonstrated the ability to penetrate seed coats and significantly influence seed germination and plant growth (Khodakovskaya *et al.* 2009). Nanoencapsulation of nutrients provides a means to deliver nutrients efficiently to plants, protecting them from leaching or volatilization and improving nutrient uptake (Sharma *et al.* 2020). Nanostructured slow-release fertilizers have been developed to enhance nutrient management in agriculture, allowing controlled and sustained release of nutrients over time, reducing nutrient loss and optimizing plant uptake (Hu *et al.* 2021). Nanosensors offer precise detection and monitoring of nutrient levels in plants, enabling real-time monitoring and targeted nutrient management (Panchal and Roy, 2018). Nanopesticides have been explored for nutrient delivery and pest management, where nanoscale formulations have been reported to enhance nutrient availability and facilitate targeted delivery of pest control agents (Khodakovskaya *et al.* 2011). Additionally, the development of nano fertilizers involves the design of nanoscale formulations that can improve nutrient availability, uptake, and utilization by plants, enhancing their overall growth and productivity (Roy *et al.* 2021). These examples illustrate the potential of nanotechnology in revolutionizing crop nutrition, improving nutrient utilization efficiency, and enhancing overall plant growth and productivity.

Plants thrive on the exact nutrients they need, where nutrient losses are minimized, and where environmental sustainability is at the forefront of agriculture. Nanotechnology offers a tantalizing glimpse into this future. It opens doors to a world where crop nutrition becomes an art of precision, a symphony of nutrients orchestrated to perfection. But like any powerful tool, nanotechnology also comes with responsibility. As we explore its potential, we must tread carefully, ensuring the safe and responsible use of nanomaterials in agriculture. Scientific research and rigorous testing are vital to understanding the long-term impacts and potential risks associated with nanotechnology.

5.2 Power of Biological Innovations in Crop Nutrition

Biological innovations equally play a significant role in advancing crop nutrition. The soil microbiome refers to the community of microorganisms, including bacteria, fungi, archaea, viruses, and other microbes, that inhabit the soil environment. These microorganisms play essential roles in soil health, nutrient cycling, organic matter decomposition, and plant-microbe interactions. They contribute to various ecosystem functions and have a significant impact on soil fertility, plant growth, and overall ecosystem dynamics (Ritz *et al.* 2021). The advancements in ***soil microbiome*** research have shed light on the crucial role of beneficial microorganisms in promoting nutrient availability and plant health. The hidden world beneath our feet holds secrets that are reshaping the way we think about crop nutrition. Soil microbiome research has unveiled the extraordinary role of beneficial microorganisms in orchestrating the dance of nutrients in the soil, promoting plant health, and unlocking the full potential of our crops. The realm of biological innovations in crop nutrition with tiny allies bring big transformations to our fields. Plant growth-promoting rhizobacteria and mycorrhizal fungi are the champions of this microbial league. These benevolent microorganisms establish symbiotic relationships with plants, delving into the intricate network of roots and soil. They become guardians of the soil ecosystem, boosting nutrient uptake, improving soil structure, and warding off harmful invaders (Singh *et al.* 2011). In this microbial ballet, rhizobacteria perform astonishing feats. They produce hormones that stimulate root growth, increasing the surface area for nutrient absorption. They solubilize phosphorus, unlocking its potential for hungry plants. They even engage in chemical warfare, releasing antimicrobial compounds to fend off pathogens that threaten the delicate balance

of the rhizosphere (Vessey, 2003).
Mycorrhizal fungi, another symbiotic partner of plants, form a remarkable bond with their green companions (Smith and Read, 2008). In return for shelter and sustenance, these fungi provide plants with a treasure trove of nutrients. They scavenge phosphorus from the depths, unlocking the locked. They scuttle through the soil, absorbing water and micronutrients like tiny nutrient miners and become the conduit through which plants tap into hidden resources, gaining resilience and vigor.

The story, however, does not end there as biological innovations in crop nutrition have birthed a new era of eco-friendly solutions. The use of biofertilizers is becoming the champions of sustainable agriculture which is derived from microbial sources. Biofertilizers are biological agents that contain beneficial microorganisms, such as bacteria, fungi, or archaea, which enhance nutrient availability and plant growth. They are used as alternatives or supplements to chemical fertilizers, promoting sustainable agriculture and reducing environmental impacts. Biofertilizers can improve soil fertility, nutrient cycling, and plant nutrient uptake through various mechanisms, including nitrogen fixation, phosphorus solubilization, and production of growth-promoting substances (Nascimento *et al.* 2018). These natural wonders offer an alternative to chemical fertilizers, reducing environmental impacts while promoting soil health. Biofertilizers harness the power of microorganisms, packed with the potential to unlock nutrient cycling and maximize nutrient uptake efficiency. These beneficial microbes come in different forms, from microbial inoculants to consortia of carefully selected strains. They enter the scene, bringing their microbial magic to the roots of the crops. Biofertilizers enhance nutrient availability, breaking down organic matter, and releasing locked nutrients into the waiting arms of hungry plants. They create a haven for beneficial soil organisms and nurturing a thriving soil ecosystem.

In the world of genetic engineering and biotechnology, the script is also being rewritten and new possibilities unfold. Scientists wield their knowledge to engineer crop varieties with enhanced nutrient uptake and utilization efficiency. They unlock the secrets of plant genomes, discovering the genetic blueprints for improving nutrient absorption. These visionary pioneers develop crop varieties that dance gracefully with nutrients, taking up vital elements with ease and finesse. They create plants that withstand the challenges of nutrient deficiencies or toxicities, paving the way for a resilient and nourished future.

5.3 Smart Farming Systems and Crop Nutrition

Innovative farming systems, such as ***hydroponics, aeroponics***, and ***vertical farming***, have also emerged as solutions for efficient nutrient management and year-round crop production. These soilless systems provide precise control over nutrient delivery, water availability, and environmental conditions, optimizing plant growth and optimizing resource use.

Hydroponics is a farming method that involves growing plants in a soilless medium, with the roots submerged in a nutrient-rich water solution. The plants receive essential nutrients directly from the water, allowing for efficient nutrient uptake and precise control over nutrient levels. This technique enables water conservation, reduces the need for pesticides, and allows for year-round cultivation in controlled environments (Gull *et al.* 2016).

Aeroponics is also a soilless cultivation method in which plants are grown in an environment where their roots are suspended in air, and nutrient-rich mist or aerosol is periodically sprayed onto the roots. This technique promotes efficient nutrient absorption and oxygenation of the roots, leading to faster growth rates and higher yields. Aeroponics also requires less water compared to traditional soil-based farming (Hochmuth, 2019).

Another innovative farming system is vertical farming which involves cultivating plants in vertically stacked layers or vertically inclined surfaces, such as shelves or towers, utilizing artificial lighting and controlled environments. This approach maximizes land use efficiency by utilizing vertical space, and it allows for year-round production independent of traditional seasonal constraints. It offers advantages such as reduced water usage, improved nutrient management, and decreased reliance on pesticides (Despommier, 2013).

These systems involve growing plants in nutrient-rich solutions or misted environments, providing precise control over nutrient concentrations and ensuring that plants have access to all the necessary elements for their growth. Hydroponic systems, for example, supply plants with a carefully-balanced nutrient solution, allowing for maximum nutrient absorption and eliminating the need for soil. Vertical farming takes advantage of vertical space, utilizing artificial lighting and controlled environments to grow crops in stacked layers, maximizing land use efficiency and reducing the need for extensive agricultural land (Pant *et al.* 2019).

5.4 Potential of Regenerative Practices and Circular Economy in Crop Nutrition

There is a growing emphasis on sustainable and regenerative agricultural practices that aim at restoring soil health, enhancing nutrient cycling, and promoting biodiversity. Conservation agriculture is one such practice that involves minimal soil disturbance, permanent soil cover, and diversified crop rotations. By reducing or eliminating tillage, conservation agriculture helps improve soil structure, retain moisture, and reduce nutrient losses, thus enhancing soil health and fertility (Hobbs *et al.* 2008). Permanent soil cover, such as the use of cover crops, further protects the soil from erosion, enhances organic matter content, and improves nutrient cycling (Doran *et al.* 1996). Diversified crop rotations also contribute to soil fertility by breaking pest and disease cycles, improving nutrient availability, and promoting beneficial soil microbial communities (Liebman and Davis, 2000). Agroforestry systems, which combine trees and crops, offer another nature-based approach to enhance soil fertility and improve crop nutrition. Trees in agroforestry systems provide numerous benefits, including nitrogen fixation through symbiotic associations with nitrogen-fixing bacteria, which enriches the soil with available nitrogen for crops (Nair, 1993). Furthermore, trees contribute to organic matter accumulation through leaf litter decomposition, adding essential nutrients and improving soil structure (Torralba *et al.* 2016). Agroforestry systems enhance biodiversity, provide shade and wind protection, and support ecological resilience in agricultural landscapes.

These sustainable and regenerative practices not only improve crop nutrition but also contribute to climate change mitigation and ecosystem resilience. By improving soil health and nutrient cycling, these practices can reduce the reliance on synthetic fertilizers and pesticides, conserve water resources, and promote a more sustainable and resilient agricultural system.

The concept of a circular economy can be applied to crop nutrition by focusing on reducing waste, optimizing resource use, and promoting sustainable practices throughout the agricultural system. This approach aims to minimize the reliance on external inputs and maximize the efficiency of nutrient use, thereby reducing the environmental impact of agriculture and promoting long-term sustainability. Techniques such as composting, biochar application, and waste valorization contribute to nutrient recycling, transforming organic residues into nutrient-rich amendments for soil enrichment. By closing the nutrient loop, these practices minimize nutrient losses, conserve resources, and promote sustainable agricultural systems (Zavalloni *et al.* 2020). In the context of crop nutrition, the circular economy principles can be implemented through various strategies:

Nutrient recycling through utilizing organic waste, such as crop residues, animal manure, and food waste, as nutrient sources, farmers can recycle nutrients back into the agricultural system. These organic materials can be composted or processed into biofertilizers, allowing for the recovery and reuse of nutrients. Implementing closed-loop nutrient management systems involves capturing and recycling nutrients from various sources within the agricultural system. This includes adopting practices such as cover cropping, crop rotation, and intercropping to enhance nutrient cycling and reduce the reliance on synthetic fertilizers.

Precision agriculture techniques, including soil and plant nutrient sensing technologies, enable precise application of fertilizers based on the specific nutrient needs of crops. This helps minimize nutrient losses, optimize nutrient uptake, and reduce the over-application of fertilizers.

Sustainable farming practices such as conservation agriculture, agroforestry, and integrated nutrient management promote sustainable nutrient management. These practices focus on improving soil health, enhancing nutrient cycling, and reducing nutrient losses through the use of organic amendments, crop diversification, and minimal soil disturbance.

5.5 Power of Data: Precision Agriculture in Crop Nutrition

Precision agriculture is an approach that utilizes advanced technologies and data-driven techniques to optimize agricultural practices, such as nutrient management, irrigation, pest control and harvesting on a site-specific basis (Gebbers and Adamchuk, 2010). It involves the collection, analysis, and interpretation of data from various sources including remote sensing, Global Positioning Systems (GPS), and sensor technologies, to make informed and targeted decisions for improved efficiency, productivity and sustainability in farming operations. The development of ***precision***

agriculture technologies harnesses the power of data, sensors and artificial intelligence to optimize nutrient management practices. For instance, remote sensing technologies such as satellite imagery and drones, can provide valuable information about crop health, nutrient status, and yield potential. These data can be integrated with Geographic Information Systems (GIS) and GPS to create detailed nutrient application maps, enabling farmers to apply fertilizers precisely where they are needed, minimizing waste and maximizing nutrient use efficiency.

In this era of precision agriculture, there is an increase in the application of remote sensing technologies which help in capturing images that reveal a hidden world of crop health, nutrient status and yield potential. Satellites orbiting high above earth, and agile drones buzzing through the skies become the 'eyes' in the sky, painting a vivid picture of the agricultural landscapes. These remarkable technologies provide farmers with invaluable insights into their crops, allowing them to detect early signs of stress, nutrient deficiencies or disease outbreaks. With this aerial perspective, farmers gain a holistic understanding of their fields, empowering them to make informed decisions for optimized nutrient management (Shen *et al.* 2019; Ge *et al.* 2021).

Integrating the data collected through remote sensing with GIS and GPS, farmers can create detailed nutrient application maps that guide them in applying fertilizers with surgical precision. No longer are nutrients dispersed haphazardly across vast expanses of land. Instead, they are applied precisely where they are needed, like brushstrokes of nourishment across a canvas. This targeted approach minimizes waste, reduces the risk of nutrient runoff, and maximizes the efficient use of resources (Yang *et al.* 2020).
A farmer equipped with this wealth of information, and the attendant ability to analyze crop health and monitor nutrient status, will predict yield potential with unprecedented accuracy. Armed

with data-driven insights the farmer can make timely interventions and adjust nutrient applications in real-time to address specific crop needs. This is a revolution that transcends traditional farming practices, ushering in a new era where every decision is driven by data and guided by precision.

Powerful algorithms analyze vast amounts of data through artificial intelligence, identifying patterns and correlations that are beyond the reach of human capabilities. By learning from historical data and real-time observations, these intelligent systems provide farmers with actionable recommendations, suggesting optimal nutrient management strategies tailored to each specific field. It is a partnership between human expertise and digital intelligence, where the boundaries of what is possible in agriculture are pushed further than ever before.

In this brave new world of precision agriculture, farmers become true stewards of the land, leveraging data-driven insights and advanced technologies to nurture their crops with unrivaled efficiency. Embracing precision agriculture helps to embark on a journey towards sustainable farming practices that optimize resource use, minimize environmental impact, and ensure the long-term viability of our food production systems.

5.6 Biofortification in Crop Nutrition

One of the remarkable advancements in crop nutrition is the concept of ***biofortification*** which seeks to enhance the nutritional content of crops to address specific nutrient deficiencies in populations. Biofortification offers a promising strategy to combat widespread micronutrient deficiencies, also known as hidden hunger, that affect millions of people around the world. The role of crop nutrition extends beyond the growth and productivity of crops. It also influences the nutritional quality of crops and subsequently impacts human health. Adequate nutrient availability in crops ensures that they contain the essential vitamins, minerals and other bioactive compounds necessary for a balanced diet. Consequently, crop nutrition plays a significant role in mitigating malnutrition, supporting immune function, and reducing the risk of diet-related diseases.

Biofortification stands as a testament to human determination and compassion. It is a powerful strategy that aims at enriching the nutritional content of staple crops, infusing them with essential micronutrients that are often lacking in the diets of millions. Like superheroes of the soil, these biofortified crops carry the potential to vanquish the scourge of nutrient deficiencies that plague vulnerable populations. By boosting the levels of vital nutrients, such as iron, zinc and vitamin A in crops that are central to the diets of millions, biofortification unlocks a sustainable and cost-effective solution to address hidden hunger. It integrates nutrient enhancement directly into the food system, bridging the gap between agriculture and public health, and nourishing those who need it most (Bouis *et al.* 2017).

Biofortified crops have the potential to make a significant impact on public health by providing essential nutrients to vulnerable populations who have limited access to diverse diets or rely heavily on staple crops for sustenance. Biofortified crops, such as cassava and sweet potato, offer a promising solution to address malnutrition and nutrient deficiencies in Nigeria. These crops have been bred to have higher levels of essential vitamins and minerals, providing improved nutritional value compared to their conventional counterparts. In Nigeria, biofortification efforts have focused on crops like vitamin A-rich cassava and orange-fleshed sweet potato which are rich sources of pro-vitamin A carotenoids. Studies have shown that the consumption of biofortified cassava and sweet potato can contribute to increased vitamin A intake and improved nutritional status among vulnerable populations (Egesi *et al.* 2012; Sanoussi *et al.* 2021). These biofortified crops hold great potential in combating malnutrition and promoting food security in Nigeria, where vitamin A deficiency remains a significant public health concern. By increasing the nutrient content of commonly consumed crops, biofortification offers a sustainable and cost-effective approach to address nutrient deficiencies, as it integrates the nutrient enhancement directly into the food system. Biofortification, in particular, holds great promise in combating nutrient deficiencies, improving the health and well-being of populations dependent on staple crops. By integrating biofortification with other crop nutrition management practices such as soil fertility management, crop rotation, integrated nutrient management, and precision agriculture, we can maximize crop productivity, promote food security and contribute to a healthier and more resilient food system.

Generally, innovations in crop nutrition offer tremendous opportunities to optimize nutrient availability, enhance crop productivity, and promote sustainability in agriculture. From precision agriculture technologies to nanotechnology, biological innovations, alternative farming systems, and sustainable practices, these advancements are reshaping the way we approach crop nutrition. By harnessing the power of science, technology and nature-based solutions, we can meet the challenges of feeding a growing population, and revolutionize traditional agricultural practices while safeguarding the environment and ensuring a resilient and sustainable food system.

6.0 PRINCIPLES AND PRACTICES OF CROP NUTRITION MANAGEMENT

Crop nutrition management refers to the application of nutrients to crops to optimize their growth, yield and quality. It involves a deep understanding of the chemical, biological and physical properties of the soil and the plant, as well as the interrelationships between them. Crop nutrition management also encompasses a range of practices from the use of fertilizers to the adoption of conservation agriculture techniques. The key principles of crop nutrition management are as discussed:

6.1 Soil Testing and Analysis: Unlocking the Secrets of the Earth

Soil testing is the first and most important step in crop nutrition management. It provides information about the nutrient status of the soil and helps to determine the type and amount of fertilizers needed. Imagine having the ability to decipher the hidden language of the soil, to understanding its nutrient composition and potential. Soil testing emerges as the foundational step in crop nutrition management. By analyzing soil samples, we gain invaluable insights into its nutrient status, pH levels, and physical properties. This knowledge equips us with a solid foundation upon which we can tailor our nutrient management strategies. Soil testing empowers us to make informed decisions, ensuring that we provide crops with the precise nutrients they need for optimal growth and vitality.

6.2 Nutrient Balancing: The Art of Harmonizing Nature's Elements

Balancing the nutrients in the soil is essential for optimal crop growth and development. It involves applying the right amount of each nutrient, based on the crop requirements and the nutrient availability in the soil. Just as a composer carefully orchestrates the notes of a symphony, farmers and agronomists harmonize the nutrients within the soil. Nutrient balancing lies at the core of crop nutrition management, allowing us to strike a delicate equilibrium between the nutrients available in the soil and the specific requirements of each crop. By understanding the nutrient needs of our plants and carefully assessing the soil's nutrient content, we can fine-tune our fertilizer applications. This ensures that crops receive a balanced blend of essential elements, fostering their growth, vigor, and productivity.

6.3 Matching Nutrient Supply with Crop Demand: Timing is Everything

In the intricate dance of plant growth, timing is everything. The timing and rate of nutrient application is based on the crop's growth stage and nutrient demand. This ensures that the nutrients are available when the crop needs them the most. Just as a chef knows when to add each ingredient to a culinary masterpiece, farmers synchronize nutrient supply with crop demand. Matching nutrient application with the growth stage of the crop ensures that plants receive the nutrients they require at the right time. This targeted approach maximizes nutrient uptake efficiency, optimizing plant development and yield potential. By embracing this principle, farmers become the conductors of nature's symphony, orchestrating the nutrients that nurture their crops.

6.4 Efficient Nutrient Use: Minimizing Waste + Maximizing Impact = Optimized Yield

Efficient nutrient use involves minimizing losses due to leaching, volatilization, or denitrification. This can be achieved through the use of slow-release fertilizers, precision agriculture techniques, and improved irrigation practices. In our pursuit of sustainable agriculture, minimizing nutrient losses becomes paramount. Efficient nutrient use is the guiding principle that allows us to minimize wastage due to leaching, volatilization, or denitrification. By employing innovative strategies such as slow-release fertilizers, precision agriculture techniques, and improved irrigation practices, we can reduce the environmental footprint of nutrient application. By maximizing nutrient utilization by crops, we safeguard resources, protect water quality, and cultivate a more sustainable future.

6.5 Sustainable Nutrient Management: Balancing Productivity and Preservation

Sustainable nutrient management involves adopting practices that minimize the negative impact of fertilizers on the environment such as reducing greenhouse gas emissions and minimizing nutrient runoff (Guzmán and Govaerts, 2020). As stewards of the land, we recognize our responsibility to ensure that nutrient management practices align with the principles of sustainability. Sustainable nutrient management requires us to adopt practices that minimize the negative impact of fertilizers on the environment. Through the reduction of greenhouse gas emissions, the prevention of nutrient runoff, and the preservation of soil health, we harmonize agricultural productivity with environmental preservation. By nurturing the delicate balance between productivity and preservation, we cultivate a future where agriculture thrives in harmony with the natural world.

6.6 Integrated Nutrient Management: Embracing Nature's Wisdom

Integrated nutrient management involves using a combination of organic and inorganic fertilizers, crop residues, and cover crops to enhance soil fertility and improve nutrient use efficiency. Nature, in its wisdom, provides us with a tapestry of solutions for sustainable nutrient management. Integrated nutrient management draws upon this wisdom by combining the use of organic and inorganic fertilizers, crop residues, and cover crops. By harnessing the power of organic matter, we enhance soil fertility, improve nutrient retention, and nurture the microbial communities that sustain plant health. This holistic approach fosters a virtuous cycle, where the outputs of one season become the inputs for the next, as we honor the cyclical rhythm of nature.

6.7 Site-Specific Nutrient Management: Precision in the Field

Site-specific nutrient management involves tailoring nutrient management practices to the specific soil and climate conditions of a given location. This can be achieved through the use of precision agriculture technologies such as soil sensors and remote sensing. Just as each landscape holds its own unique beauty, each field possesses distinct soil and climate conditions. Site-specific nutrient management recognizes this diversity, and tailors nutrient management practices to the specific needs of each location. Through the use of cutting-edge precision agriculture technologies, such as soil sensors and remote sensing, we gain a granular understanding of the variability within fields. Armed with this knowledge, we can apply nutrients precisely where they are needed, optimizing resource use and maximizing crop performance.

Generally, principles and practices of crop nutrition management lay the foundation for sustainable agriculture, bridging the gap between plant nutrition and human nutrition. By embracing these principles and implementing transformative practices, we empower ourselves to cultivate resilient farming systems that sustainably nourish both the earth and its inhabitants. Together, we can forge a future where the intricate dance of plant nutrition and human nutrition intertwine harmoniously, fostering a world of abundance, health, and well-being for all.

7.0 MY RESEARCH CONTRIBUTIONS TO CROP NUTRITION

Mr Vice-Chancellor, Sir, my research career started when the concept of sustainability was placed in the front burner in Agricultural research in the tropics. International Institute of Tropical Agriculture (IITA) became a major player and coordinated the National Agricultural Research System in Nigeria and many African countries. This provided opportunities for many of us to develop our research potential which had become the pivot of our growth till now. My first major work was on the need to make alley farming more efficient in the dynamics of nutrients available to intercrops. Alley farming, also known as alley cropping is an agroforestry system that combines tree planting with annual or perennial crop cultivation. Kang, a distinguished soil scientist at the IITA is widely recognized for his expertise in soil science and has conducted extensive research on agricultural practices, particularly focusing on alley cropping systems and their impact on nutrient utilization and soil health. Kang's work has shed light on sustainable agricultural techniques that optimize nutrient retention and minimize losses through innovative approaches. Beyond the findings mentioned in the Vander Merch and Mulongoy study in 1988, Kang explored various factors influencing nutrient dynamics in agroecosystems, including soil amendments, crop rotations, and management practices aimed at improving overall crop productivity and environmental sustainability. Alongside the nutrient loss, the underground water is getting polluted, the atmosphere is filled with greenhouse gasses, aquatic lives are getting endangered, human health deteriorates and the circle of the effects of global warming continues.

My research efforts took cognisance of these and was focused at paying attention to the need for appropriate "feeding" of plants through well-adjudged nutrient supply and utilization. These efforts are under the following subheads:

1) Exploring the symbiotic relationship between crops and Mycorrhizal Fungi
2) Exploring the impact of carbon dioxide enrichment and Arbuscular Mycorrhizal (AM) Fungi on crop nutrition
3) Assessing the role of crop nutrition in enhancing stress tolerance in crops
4) Integrated nutrients management in crop production

7.1 Exploring the symbiotic relationship between crops and Mycorrhizal Fungi

The symbiotic relationship between crops and AM fungi is a fascinating partnership that enhances nutrient availability for plants. The AM fungi establish connections with crop roots, facilitating the exchange of nutrients, particularly phosphorus, from the soil. In return, crops provide carbon compounds to support the growth of AM fungi. This relationship goes beyond nutrient exchange, as AM fungi also contribute to improved plant health, stress tolerance, and overall crop productivity. Understanding the mechanisms and signaling pathways involved in this symbiosis offers great potential for sustainable agriculture, enabling optimized crop nutrition management while reducing the need for synthetic fertilizers.

The assessment and evaluation of AM fungi in crop nutrition play a crucial role in understanding their potential benefits and optimizing their use in agricultural systems. Various methods such as microscopic analysis of root colonization, molecular techniques for species identification, and quantification of nutrient uptake by plants are employed to assess the presence and effectiveness of AM fungi. These assessments help gauge the extent of symbiotic associations, the diversity of AM fungal species and their impact on crop nutrient acquisition. Evaluating the efficacy of AM fungi in crop nutrition involves examining plant growth parameters, nutrient content, and overall yield in comparison to non-mycorrhizal systems. Additionally, assessing the compatibility of different AM fungal species with specific crops and soil conditions is essential for effective implementation. Through comprehensive assessment and evaluation, we gain insights into the role of AM fungi in enhancing crop nutrition, paving the way for informed decision-making and sustainable agricultural practices.

As a researcher in this field, I have dedicated my career to understanding the potential of these organisms to enhance crop nutrition and promote sustainable agriculture. The fungi form symbiotic associations with the roots of most plants. These fungi are found in nearly all types of soils and are essential for the growth and survival of many plant species, including important crops like maize, cassava, and rice. The AM fungi are capable of improving plant nutrient uptake, particularly for nutrients like phosphorus that are often limiting in soils. They do this by extending their hyphae (thread-like structures) into the soil, where they can access and absorb nutrients that are otherwise unavailable to the plant. The nutrients are then transported to the plant roots, where they are used for growth and development.

7.1.1 Studies on the use of mycorrhizal fungi on nutrient uptake and crop productivity in alley cropping systems

In a study conducted in year 2000 on the effect of Vesicular Arbuscular Mycorrhizal (VAM) inoculation on nutrient uptake by hedgerow trees: *Senna* sp., *Gliricidia* sp., and *Leucaena* sp., the results show that VAM inoculation increased nutrient uptake in woody legumes (Table 2). VAM-inoculated trees had significantly higher uptake of phosphorus, potassium, and magnesium compared to uninoculated trees at both the top and base of the slope.

By improving nutrient uptake and cycling, mycorrhizal fungi contributed to more efficient nutrient utilization by crops, reducing the need for synthetic fertilizers and minimizing environmental impacts (Atayese *et al.* 2005). However, it was also noted that the effect of VAM inoculation varied depending on the location of the hedgerow trees - those at the base of the slope showed greater survival and higher leaf dry weights than those at the top of the slope.

Table 2: Effect of VAM inoculation on nutrient uptake (kg ha $^{-1}$) by hedgerow trees at top and base of slope 12 months after planting

Tree species	Treatment	P	N	K	Ca	Mg
Senna sp.	Top M+	2.7b	39.1c	19.8ab	35.5a	2.7b
	M-	2.0b	33.8c	12.9b	32.8a	2.4b
	Base M+	4.7a	81.9a	30.0a	38.2a	6.5a
	M-	2.4b	58.7b	13.6b	20.8a	2.5b
Gliricidia sp.	Top M+	4.1b	75.2b	49.7a	46.7a	10.9a
	M-	2.0c	32.7c	27.2b	16.3b	4.2b
	Base M+	6.4a	117.7a	60.7a	28.0ab	10.9a
	M-	3.0b	65.0b	25.2b	20.1b	7.3ab
Leucaena sp.	Top M+	5.7b	122.8b	75.4ab	87.8a	14.3b
	M-	2.7c	60.7c	34.9b	36.0a	9.0b
	Base M+	11.7a	203.7a	111.8a	50.2a	23.2a
	M-	3.7b	128.2b	31.4b	39.2a	15.4b

M+ Inoculated, M- uninoculated, Means followed by different letters are significantly different ($P < 0.05$) according to Duncan's Multiple Range Test DMRT
Source: Atayese *et al.* 2005

Another study was conducted to observe the long-term effect of VAM inoculation and hedgerow prunings added to the soil in the 2nd, 3rd, and 4th years after planting. It was observed that the nutrient yield of N, P and K, as well as percent fungal colonization of the hedgerow tree roots in the inoculated tree species increased as shown in Table 3 and 4 respectively. The extensive networks of hyphae enhance soil aggregation, improve water infiltration, and increase organic matter decomposition. This promotes nutrient cycling, reduces nutrient leaching, and enhances overall soil health which, in turn, supports crop growth and productivity.

In an effort to find out the effects of mycorrhizal inoculation on continuous hedgerow-biomass production and nutrient contribution to alley-cropped cassava in Nigeria, a study was conducted in 1990 over four consecutive cropping seasons in an alley-cropping plot established on a hill-slope at Ajibode village near the University of Ibadan. The results showed that inoculation with *Glomus deserticolum* promoted hedgerow leaf-biomass and nutrient (N, P, and K) production which resulted in increased yield of cassava (Table 5).

The study suggests that mycorrhizal inoculation enhances biomass production of hedgerow trees and nutrient contribution to alley-cropped cassava in Nigeria (Osonubi *et al.* 1994). Overall, the use of mycorrhizal fungi in alley cropping systems offers promising opportunities for sustainable and productive agroforestry practices. By enhancing nutrient availability, improving soil structure and increasing crop resilience, mycorrhizal fungi contribute to improved crop productivity and environmental sustainability in these integrated cropping systems. Incorporating mycorrhizal fungi into alley cropping practices enhances nutrient cycling, reduces input requirements and promotes more resilient and productive agroecosystems.

Table 3: Nutrient yield of inoculate and uninoculated hedgerow prunings added to the soil in the 2 nd, 3rd and 4th year of alley cropping at Ibadan, Nigeria

Year of cropping	Inoculation treatment	Nutrient yield (kg/ha)								
		Leucaena			*Gliricidia*			*Senna*		
		N	P	K	N	P	K	N	P	K
2-month pruning regime										
2nd	M+	430a	22.0a	245a	425a	24.5a	290a	200a	14.5a	99a
	M-	260b	14.5b	150b	238b	11.5b	155b	150b	10.5b	65b
3rd	M+	290a	17.0a	205a	355a	21.0a	300a	155a	9.5a	85a
	M-	250b	16.5a	135b	310b	18.5a	250b	145a	9.0a	60b
4th	M+	350a	22.2a	180a	245a	15.1a	145a	175a	20.0a	40a
	M-	315b	22.4a	175a	246a	15.7a	148a	175a	20.8a	41a
3-month pruning regime										
2nd	M+	450a	21.5a	214a	295a	17.0a	180a	250a	16.0a	120a
	M-	270b	8.5b	151b	150b	7.0b	100b	170b	10.0b	70b
3rd	M+	260a	13.5a	165a	205a	10.5a	115a	90a	7.5a	35a
	M-	255a	10.3b	150a	155b	7.5b	9.5b	90a	9.8a	20a
4th	M+	345a	22.3a	180a	235a	16.5a	147a	200a	20.5a	45a
	M-	345a	21.5a	175a	234a	16.8a	145a	201a	19.8a	46a

M+ Inoculated, M- uninoculated, Means within same year followed by different letters are significantly different ($P < 0.05$) according to Duncan's Multiple Range Test DMRT
Source: Liasu *et al.* 2005

Table 4: Effect of AM inoculation on fungal colonization of hedgerow tree roots at the end of each cropping year at Ibadan, Nigeria

Year of cropping	Inoculation treatment	% fungal colonization of hedgerow tree roots		
		Leucaena	*Gliricidia*	*Senna*
2-month pruning regime				
2nd	M+	33c	50b	19d
	M-	26f	28c	17d
3rd	M+	52a	55a	30a
	M-	37d	36d	21c
4th	M+	48b	42c	26b
	M-	40c	35d	25b
3-month pruning regime				
2nd	M+	57c	62c	25c
	M-	32f	35c	22d
3rd	M+	68a	70a	30b
	M-	50d	48d	21d
4th	M+	65b	68b	45
	M-	40c	30f	25c

M+ Inoculated, M- uninoculated, Means within the same hedgerows at each pruning regime followed by different letters are significantly different ($P > 0.05$) according to Duncan's Multiple Range Test DMRT
Source: Liasu *et al.* 2005

Table 5: Leaf and root dry weight and nutrient uptake by inoculated (M+) and uninoculated (M-) alley-cropped and sole cassava (ND not determined)

Cassava alley - cropped with	Cassava part	Year	Dry weight (t ha^{-1})		Nutrient uptake (kg ha^{-1})					
					N		P		K	
			M^+	M^-	M^+	M^-	M^+	M^-	M^+	M^-
Gliricidia sp.	Leaf	1	1.6c	1.0c	38.1a	29.1a	2.1a	1.3b	13.8a	9.1a
		2	3.0a	2.2b	40.3a	31.2a	23.a	1.5b	12.2a	8.3a
		3	3.2a	2.4b	43.2a	35.7a	2.7a	1.5b	15.3a	11.6a
	Root	1	4.2c	3.0c	ND	ND	ND	ND	NMD	ND
		2	7.8b	4.4c	40.6a	18.0b	7.8b	4.4c	75.7b	28.6c
		3	10.5a	5.1c	57.8a	20.4b	13.7a	5.6c	102.9a	36.2c
Leucaena sp.	Leaf	1	1.6c	1.1c	37.4a	30.1a	2.6a	1.1b	14.5a	9.3ab
		2	2.8a	2.2b	39.3a	32.5a	2.3a	1.3b	12.5a	8.1b
		3	3.3a	2.5b	42.5a	35.4a	2.8a	1.3b	15.4a	11.3a
	Root	1	4.3b	3.1b	ND	ND	ND	ND	ND	ND
		2	7.8a	4.4b	39.0a	16.3b	8.6b	3.5c	68.6a	27.7b
		3	8.6a	5.0b	44.7a	18.0b	12.6a	5.4c	79.1a	31.5b
Senna sp.	Leaf	1	1.4b	1.0b	32.0a	28.6a	1.8a	1.0a	12.1a	8.1a
		2	2.2b	1.5b	35.1a	34.5a	2.0a	2.0a	10.4a	6.8a
		3	2.4a	1.7b	39.1a	36.2a	2.0a	2.1a	12.1a	8.3a
	Root	1	3.8b	2.7b	ND	ND	ND	ND	ND	ND
		2	6.4a	3.5b	23.1a	11.2b	6.4a	2.8b	11.5a	8.8a
		3	6.0a	3.4b	19.2a	9.5b	6.6a	2.4b	13.2a	9.9a
Sole cassava	Leaf	1	1.4c	1.0c	33.4a	25.2a	1.2b	1.0b	6.5a	5.2a
		2	3.2a	2.4b	37.1a	30.6a	1.9a	1.6a	10.1a	7.5a
		3	2.5b	2.0b	33.2a	27.0a	1.7a	1.5ab	8.2a	6.5a
	Root	1	4.6b	2.8b	ND	ND	ND	ND	ND	ND
		2	8.2a	5.2b	27.9a	15.1a	8.2a	4.2b	12.3a	13.0a
		3	5.2b	3.6b	16.1a	11.5a	4.7b	2.5b	9.4a	6.5a

Mean values for dry weight of each nutrient and for each cassava part within each plant species followed by different letters are significantly different at $P > 0.05$ according to Duncan's Multiple Range Test
Source: Osonubi *et al.* 1994

7.1.2 Studies on Influence of native AMF species on the efficiency of fertilizer use in crop production

In our study conducted in Nigeria's sub-humid zone where soil fertility sustenance is a major constraint to crop production in year 2010, the combination of *Glomus* species and Sokoto rock phosphate significantly increased soybean yield and nutrient uptake compared to the control treatment (Table 6). The study confirmed that *Glomus* species enhances the fertilizer efficiency of Sokoto rock phosphate by improving plant nutrient uptake and yield. Using *Glomus* species in conjunction with phosphate rock is an effective strategy for improving crop yields and soil fertility in resource-poor regions (Babalola *et al.* 2010).

We conducted a study on inoculation of soybean cultivars with the highly efficient AMF strains (*F. mosseae*, C. *etunicatum* and *R. intraradices*) in 2017 and 2018 under field conditions. The results showed that the mycorrhizal inoculations had a significant effect on the number of pods per plant, 100-seed weight, straw yield, and grain yield. The highest grain yield was observed in the *R. intraradices* treatment, followed by the *F. mosseae* treatment, while the control (uninoculated) group had the lowest yield (Table 7). Furthermore, we observed that the mycorrhizal inoculations had a significant effect on shoot P uptake, grain P uptake, total P uptake, PAE, and PUE (Table 8). The highest values for these parameters were observed in the *R. intraradices* treatment, followed by the *F. mosseae* treatment, while the control group had the lowest values. The R. intraradices treatment was found to be the most effective in improving grain yield and phosphorus uptake, followed by the *F. mosseae* treatment.

Table 6: Effect of AMF and PR pm soil residual N, P, organic matter and Mycorrhiza spores

Treatments	N (%)	P (mg/kg)	SOM (%)	Mycorrhiza soil	Spore/100g
				3 WAS	9 WAS
G *mosseae*	0.82	8.6	0.42	38.3	61.0
G *deserticola*	0.2	8.8	0.59	39.3	70.3
PR	0.09	7.3	0.18	35.7	52.0
Mosseae/PR	0.99	8.3	0.46	52.0	83.7
Deserticola/PR	0.88	8.4	0.53	49.0	85.0
SSP	0.36	11.7	0.50	31.0	33.7
Control	0.19	6.9	0.30	31.7	44.7
LSD (0.05)	0.252	0.838	0.133	6.369	19.408

Source: Babalola *et al.* (2010)

Table 7: Effect of mycorrhizal inoculations on grain yield and yield components of soybean cultivars under field conditions (averaged across 2017 and 2018 growing seasons)

Cultivars	AMF treatment	Number of pods per plant	100-seed weight (g)	Straw yield (kg ha-1)	Grain yield (kg ha-1)	MIE (%)
TGx 1440-1E	F. *mosseae*	58.5bc	7.9bc	1675.5b	2306b	44.2a
	R. *intraradices*	68.8ab	9.14a	2002a	2340.5b	44.9a
	C. *etunicatum*	57.2cd	7.80bc	1652b	1893.5c	32b
	AMF control	40.9f	7.08cd	1370cd	1287.5d	-
	P. fertilizer	60.0bc	7.46cd	2061.5a	2715a	-
TGx 1448-2E	F. *mosseae*	53.5de	7.6bcd	1653.5b	2475.5b	45.6a
	R. *intraradices*	58.9b	8.43ab	1793.5b	2475b	45.5a
	C. *etunicatum*	45.6e	7.41cd	1543.5bc	1958c	31.2b
	AMF control	37.8f	6.86d	1238d	1347.5d	-
	P. fertilizer	72.9a	9.24a	2101a	2782a	-
	SEm (+)	11.4	0.88	224.6	172.9	9.13

Means with different letters are significantly different at 5% probability level according to Duncan's multiple range test (n = 3), MIE: Myccorhizal inoculation effect
Source: Adeyemi *et al.* 2021

Table 8: Effect of mycorrhizal inoculations on phosphorus uptake, PAE and PUE of soybean cultivars under field conditions (averaged across 2017 and 2018 growing seasons)

Cultivars	AMF treatment	Shoot P uptake (kg ha^{-1})	Grain P uptake (kg ha^{-1})	Total P uptake (kg ha^{-1})	PAE	PUE (kg kg^{-1})
TGx 1440-1E	F. *mosseae*	14.0^{d}	13.8^{d}	27.8^{bcd}	0.68ab	84.2^{a}
	R. *intraradicess*	17.2^{bc}	15.0^{cd}	30.2^{bc}	0.73^{a}	77.7a
	C. *etunicatum*	13.2^{d}	13.7^{d}	26.8^{cd}	0.65^{bc}	71.3^{b}
	AMF control	11.3^{e}	10.9^{c}	20.6^{e}	0.49^{d}	63.1^{c}
	P. fertilizer	19.1^{a}	21.2^{a}	41.3^{a}	-	-
TGx 1448-2E	F. *mosseae*	18.7^{ab}	17.7^{b}	30.8^{b}	0.72^{a}	80.9^{a}
	R. *intraradicess*	17.9^{ab}	16.2^{bc}	29.9^{bc}	0.70^{ab}	83.3^{a}
	C. *etunicatum*	16.9^{e}	14.6^{cd}	25.6^{d}	0.60^{c}	77.0^{ab}
	AMF control	11.4^{e}	9.7^{e}	19.1^{e}	0.45^{d}	70.7b
	P. fertilizer	18.3^{ab}	21.9^{a}	42.6^{a}	-	-
	SEm (+)	1.54	2.63	3.59	0.05	7.83

Means with different letters are significantly different at 5% probability level according to Duncan's multiple range test (n = 3), PAE: phosphorus acquisition efficiency PUE: phosphorus use efficiency
Source: Adeyemi *et al.* 2021

Overall, the findings of the studies presented in suggest that mycorrhizal inoculations can significantly improve the growth and yield of soybean cultivars under field conditions by enhancing nutrient uptake and use efficiency (Adeyemi *et al.* 2021). This suggests that inoculation with *highly effective AMF species* is a crucial way to improve P use efficiency and grain yield in soybean production and is crucial to establish potential local formulation of AMF inoculants using such strains in P-deficient soils.

A similar study was conducted to evaluate the combination of AMF and P fertilizers on yield performance and nutrient use efficiency in soybean in 2017 and 2018 (Table 9).

Table 9: Effect of arbuscular mycorrhizal fungi inoculation and phosphorus fertilizer application on grain yield, shoot biomass and P uptake and use efficiency of soybean cultivars in 2017 and 2018 late cropping seasons

	Shoot biomass (kg ha^{-1})		Grain yield (kg ha^{-1})		P uptake (kg ha^{-1})		P use efficiency (kg kg^{-1})	
	2017	2018	2017	2018	2017	2018	2017	2018
Cultivars								
TGx 1440 1E	1459	1742	1924	1939	16.4	19.4	27.2	29.7
TGx 1448 2E	2011	1935	2228	2281	15.4	17.4	23.2	26.2
LSD (5%)	495.9	NS	NS	NS	NS	NS	NS	NS
P rates (P_2O_5)	1266	1366	1378	1344	11.8	12.3	-	-
0kg ha^{-1}	1900	2070	2304	2400	16.8	20.5	46.3	52.8
20 kg ha^{-1}	2038	2079	2546	2586	19.1	22.4	29.2	31.1
40 kg ha^{-1}	189.3	214.2	175.6	79.5	1.78	3.15	2.59	2.97
LSD (5%)								
AMF isolates	1478	1609	1698	167.4	10.9	15.4	18.2	17.1
Control	1948	1956	2387	2429	17.6	19.3	30.8	34.2
F. *mosseae*	1874	2029	2319	2485	17.1	19.6	32.3	41.3
R. *intraradices*	1670	1759	1899	1852	17.9	19.3	19.3	19.2
C. *etunicatum*	143.7	171.0	122.3	144.0	1.51	1.74	2.03	4.59
LSD (5%)								

NS = Not Significant at $P < 0.05$
Source: Adeyemi *et al.* 2022

The findings confirmed that both AMF inoculation and P fertilizer application have a positive impact on the growth and yield of soybean cultivars in late cropping seasons. The study found that the combination of AMF

inoculation and P fertilizer application was the most effective in improving grain yield and shoot biomass, while P fertilizer application alone was the most effective in improving P uptake (Adeyemi *et al.* 2022). The results of the study are consistent with previous research that has shown the beneficial effects of AMF inoculation and P fertilizer application on plant growth and yield. Interestingly, the study did not find a significant effect of these treatments on P use efficiency. Phosphorus use efficiency is a measure of how effectively plants use P to produce biomass, and it is an important parameter for sustainable agriculture. The lack of a significant effect on P use efficiency suggests other factors such as the availability of other nutrients or environmental factors that limit the efficiency of P use in soybean cultivars.

7.1.3 Studies on effect of commercial arbuscular mycorrhizal fungi inoculant on growth and yield of soybean under controlled and natural field conditions

In recent years, interest in AM fungi has focused on finding a viable and sustainable method with a high potential to increase crop yields to increase crop yields and optimize the production of AM fungi inoculum to be used as inoculant in agricultural systems. We conducted a study in 2015 using a commercial inoculant (Empathy Mycorrhizal Rootgrow™) on growth and yield performance of soybean under controlled and natural field conditions. The results showed that AMF inoculation have a positive impact on some of the yield attributes of soybean, but the effect varied depending on the cultivar and the experimental conditions. In the controlled environment, AMF inoculation significantly increased the number of pods and the number of seeds per pod in TGx 1448-2E and TGx 1440-1E, but not in TGx 1740-2F (Table 10). Similarly, on the field study, AMF inoculation significantly increased the number of pods per plant and the number of seeds per pod in TGx 1448-2E and TGx 1440-1E, but not in TGx 1740-2F (Table 11). These findings are consistent with previous research that has shown the beneficial effects of AMF inoculation on plant growth and yield. However, the effectiveness of AMF inoculation depends on several factors, such as the specific AMF species, the plant species, the soil type, and the environmental conditions (Adeyemi *et al.* 2020).

Table 10: Yield attributes of soybean as affected by AMF inoculation and cultivar at harvest (pot experiment)

Treatments	Number of pods	Number of seeds per pod	Dry pod weight (g)	100-seed weight (g)	Dry biomass (g)	Seed yield per plant (g)
Cultivars						
TGx 1448-2E	35.8[a]	2.75[a]	12.9[a]	8.33[a]	22.4[a]	8.44[a]
TGx 1440-1E	34.0[a]	2.38[b]	12.3[a]	7.51[a]	20.6[a]	6.03[b]
TGx 1740-2F	31.0[a]	2.53[ab]	12.1[a]	6.75[a]	21.7a	5.37[b]
LSD	ns	0.27*	ns	Ns	ns	1.83**
Mycorrhizal fungi						
Inoculated	36.4[a]	2.51[a]	14.2[a]	8.63[a]	25.2[a]	8.05[a]
Uninoculated	30.8[b]	2.60[a]	10.6[b]	6.43[b]	17.9[b]	5.18[b]
LSD	4.8*	ns	2.06**	1.14**	1.68**	1.49**
C x M	ns	ns	Ns	Ns	2.91**	2.58**

Means with different letters in the same column are significantly different from each other; and indicates significance at P < 0.05 and P < 0.01 probability level respectively; ns = non-significant
Source: Adeyemi *et al.* 2020

Table 11: Yield attributes of soybean as affected by AMF inoculation and cultivar at harvest (field experiment)

Treatments	Number of pods	Number of seeds per pod	Dry pod weight (g)	100-seed weight (g)	Dry biomass (g)	Seed yield (kg ha^{-1})
Cultivars						
TGx 1448-2E	38.2	2.75^{a}	16.5^{a}	10.8^{a}	37.5^{a}	2353^{a}
TGx 1440-1E	37.7	2.47^{b}	14.0^{a}	9.22^{a}	33.1^{ab}	1818^{ab}
TGx 1740-2F	32.2	2.58^{ab}	12.1^{a}	8.97^{a}	28.0^{b}	1493^{b}
LSD	4.02**	0.19*	ns	Ns	5.5**	545.9**
Mycorrhizal fungi						
Inoculated	43.2	2.6^{a}	17.1^{a}	10.5^{a}	39.3^{a}	2439
Uninoculated	28.9	2.59^{a}	11.4^{b}	8.86^{a}	26.3^{b}	1337
LSD	3.28**	ns	2.93**	ns	4.46**	445.7**
C x M	5.68**	ns	ns	ns	ns	772**

Means with different letters in the same column are significantly different from each other; and indicates significance at $P < 0.05$ and $P < 0.01$ probability level respectively; ns = non-significant
Source: Adeyemi *et al.* 2020

7.2 Exploring the impact of carbon dioxide enrichment and Arbuscular Mycorrhizal Fungi in crop production

To study the impact of the rising atmospheric carbon-dioxide (CO_2), we conducted research in 2015 using an open-top chamber and soybean as the test crop (Plate 1). The study aimed at investigating the interactive effects of elevated CO_2 and AMF inoculation on the growth and physiology of soybean plants. The results of the study showed that both CO_2 enrichment and AMF inoculation had significant effects on the growth and physiology of soybean plants, but the effects varied depending on the cultivar and the parameter measured (Table 12). The CO_2 enrichment significantly increased the relative leaf growth rate and the relative growth rate in all three cultivars (TGx 1448-2E, TGx 1440-1E, and TGx 1740-2F), while AMF inoculation had a significant effect only on TGx 1440-1E. The net assimilatory rate, which is a measure of the efficiency of photosynthesis, was also affected by CO_2 enrichment and AMF inoculation. CO_2 enrichment significantly increased the net assimilatory rate in TGx 1448-2E and TGx 1440-1E, but not in TGx 1740-2F. The soil available N and P were also increased under CO_2 enrichment (Figure 2).

Overall, the findings from the study suggest that both CO_2 enrichment and AMF inoculation have positive effects on the growth and physiology of soybean plants, but the effects may vary depending on the cultivar and the parameter measured. The study provided insights into the mechanisms underlying the effects of CO_2 enrichment and AMF inoculation on soybean plants. The increase in the net assimilation rate in response to CO_2 enrichment suggests that the plants were able to use the additional carbon to enhance photosynthesis and growth. The increase in the relative leaf growth rate and the relative growth rate in response to CO_2 enrichment and AMF inoculation suggests that the plants were able to allocate more resources to leaf growth and biomass accumulation (Sakariyawo *et al.* 2016).

Plate 1: CO_2 enrichment in Soybean Production
Source: Adeyemi *et al.* 2020

Table 12: Effects of CO_2 enrichment and AMF inoculation on relative leaf growth rate, relative growth rate and net assimilatory ratio of soybean cultivars

	Leaf relative growth rate (g g^{-1} day^{-1})		Relative growth rate (g g^{-1} day^{-1})		Net assimilatory ratio		Grain yield (t ha^{-1})
	R1	R2	R1	R2	R1	R2	
CO2 Level (C)	0.112	0.049	0.106	0.049	0.152	0.068	1.97
Ambient	0.126	0.062	0.119	0.065	0.174	0.092	3.52
Elevated	0.012**	NS	0.01*	0.012*	0.016**	0.017**	0.44**
LSD							
AMF (A)							
Inoculated	0.121	0.065	0.114	0.064	0.163	0.086	3.01
Un-inoculated	0.181	0.046	0.111	0.051	0.162	0.074	2.48
LSD	NS	0.014*	NS	0.012*	NS	NS	0.44**
Varieties (V)							
TGx 1448-1E	0.114	0.058	0.108	0.058	0.156	0.080	2.95
TGx 1440-1E	0.122	0.058	0.116	0.058	0.165	0.078	2.65
TGx 1740-2F	0.122	0.050	0.114	0.055	0.166	0.081	2.64
LSD	NS	NS	NS	NS	NS	NS	NS
C xA	NS	NS	NS	NS	NS	NS	0.62*
C x V	NS	NS	NS	NS	NS	NS	0.77*
A x V	NS	NS	NS	NS	NS	NS	NS
C x A x V	NS	NS	NS	NS	NS	NS	1.08**

*Significant at 5% probability level, **Significant at 1% probability level, NS = Not Significant, WAP - weeks after planting, R1 = 3-6 WAP, R2 = 6 -9 WAP
Source: Sakariyawo *et al.* 2016

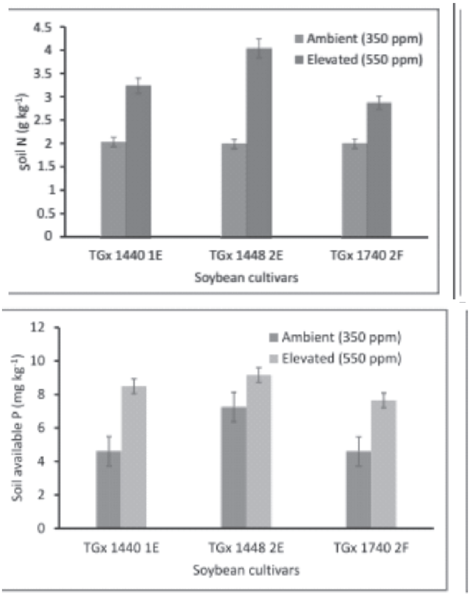

Figure 2: Dynamics of soil N (a) and available P (b) in the 0–10 cm soil layer of soybean cultivars as affected by elevated CO_2
Source: Adeyemi *et al.* 2020

7.3 Assessing the role of crop nutrition in enhancing stress tolerance in crops

*7.3.1 **Studies on the use of mycorrhizal fungi on drought tolerance***

Drought is a significant environmental stress factor that poses a substantial challenge to agricultural productivity and food security worldwide. It is characterized by a prolonged period of inadequate water availability leading to reduced plant growth, wilting, and eventual crop failure. To mitigate the negative impacts of drought on crop production, extensive research has been conducted to explore strategies for enhancing drought tolerance in plants. One approach that has shown promise is the use of mycorrhizal fungi. In the context of drought, mycorrhizal fungi play a crucial role in improving a plant's ability to cope with limited water availability.

7.3.1.1 Studies on the use of mycorrhizal fungi on drought tolerance of four leguminous woody seedlings

In a study that investigated the effects of ectomycorrhizal and vesicular-arbuscular mycorrhizal fungi on the drought tolerance of four leguminous woody seedlings, namely *Acacia auriculiformis, Albizia lebbeck, Gliricidia sepium,* and *Leucaena leucocephala,* Osonubi *et al.* (1991) inoculated the seedlings with either ectomycorrhizal or vesicular-arbuscular mycorrhizal fungi and subjected them to drought conditions (Table 13). The results of the study showed that both types of mycorrhizal fungi improved the drought tolerance of the seedlings. In particular, inoculation with mycorrhizal fungi resulted in increased leaf area, shoot and root biomass accumulation, and nutrient uptake compared to non-inoculated seedlings. We also found that different species of seedlings responded differently to the two types of mycorrhizal fungi.

Table 13: Soil moisture content, xylem pressure potential and leaf relative water content (RWC) of unstressed and drought stressed ectomycorrhizal (ECTO), vesicular-arbuscular mycorrhizal (VAM) and non-mycorrhizal (NM) leguminous woody seedlings at the end of experiment

	Soil moisture content (%)	Xylem pressure potential (MPa)	Leaf RWC (%)
Acacia auriculiformis			
Unstressed			
ECTO	20.11a	-1.38ab	94.28a
VAM	21.57a	-1.65b	92.38a
NM	20.32a	-1.15a	87.70b
Drought-stressed			
ECTO	9.68c	-2.52c	78.35c
VAM	9.68c	-2.50c	65.83c
NM	10.40b	-1.30ab	75.14d
Albizia lebbeck unstressed			
ECTO	20.63a	-1.23a	98.80ab
VAM	21.32a	-1.23a	99.36a
NM	20.90a	-1.17a	98.47bc
Drought-stressed			
ECTO	12.97b	-1.19a	98.44bc
VAM	11.97b	-1.87c	98.83ab
NM	12.69b	-1.17b	98.47bc
Gliricidia sepium unstressed			
ECTO	20.11a	-0.90a	82.72b
VAM	20.64a	-1.33ab	88.66a
NM	21.53a	-0.92a	81.17c
Drought-stressed			
ECTO	10.64b	-1.53b	77.75d
VAM	7.64c	-1.47b	77.62d
NM	7.86c	-1.50b	74.87e
Leucaena leucocephala unstressed			
ECTO	19.90a	01.82ab	83.80a
VAM	20.80a	-1.96ab	84.87a
NM	21.07a	-1.68a	83.16a
Drought-stressed			
ECTO	11.17b	-2.3bc	54.76d
VAM	8.02c	-2.73c	75.35b
NM	8.64c	-2.55c	65.48c

Means for each leguminous species within the same vertical column followed by different letter are significantly different at $P < 0.05$ according to Duncan's multiple range test

For example, *Gliricidia* and *Leucaena* had higher leaf area and shoot and root dry weights when inoculated with both

ectomycorrhizal and VAM fungi under unstressed conditions.
The findings of this study have important implications for the cultivation of leguminous woody plants in areas prone to drought. Mycorrhizal fungi could be used as a natural means to improve plant growth and survival under water-limited conditions. This is particularly relevant given the increasing frequency and severity of droughts due to climate change. Overall, this study highlights the importance of considering plant-microbe interactions in agricultural practices aimed at improving crop productivity under changing environmental conditions.

7.3.1.2 **Studies on agronomic evaluation of some drought tolerant NERICA rice varieties to AM fungi inoculation**

Developing drought-tolerant crop varieties is crucial for ensuring food security and sustainable agriculture in these areas. The NERICA (New Rice for Africa) rice varieties have gained attention for their improved drought tolerance compared to traditional rice varieties. In year 2012, we explored the potential of enhancing the drought tolerance of NERICA rice varieties through the use of AMF. The findings confirmed that AMF inoculation had a significant effect on vegetative, reproductive growth and development parameters, and the performance of NERICA 4 was significantly increased by the application of AMF inoculation (Tables 14 and 15). The positive phenotypic responses (growth and development) of upland rice varieties to AMF treatment were reflected in the yield and yield components, suggesting effective partitioning of the assimilates for AM-treated upland rice in both seasons (Sakariyawo *et al.* 2013).

Table 14: Effect of AMF inoculation on growth parameters of upland rice varieties

Treatments	Plant height (cm)			Number to tillers			Dry weight (g)		
	4 WAP	8 WAP	12 WAP	4 WAP	8 WAP	12 WAP	4 WAP	8 WAP	12 WAP
Mycorrhiza (M)									
Without	30.39b	54.04b	69.89b	2.28	2.56b	2.28b	0.44	0.82a	2.15b
With	35.11a	62.43a	83.26a	2.67	3.39a	3.00a	0.57	1.23a	2.89a
SE±	0.72	0.97	1.40	0.15	0.12	0.15	0.06	0.06	0.09
Varie ties (V)									
NERICA 1	38.32b	72.39b	92.24b	2.83a	3.50a	3.17a	0.63a	1.29ab	3.11a
NERICA 2	38.06b	65.45c	88.25b	3.17a	3.83a	3.67a	0.61a	1.15ab	3.03a
NERICA 3	39.02b	64.57b	88.29b	3.00a	3.50a	3.00a	0.53a	1.09b	2.83a
NERICA 4	38.65b	67.31c	92.99ab	2.83a	3.50a	2.83a	0.53a	1.25ab	3.14a
Moroberekan	0.00c	0.00d	0.00c	0.00b	0.00b	0.00b	0.00b	0.00c	0.00b
WAB 56 -104	42.47a	79.67a	97.67a	3.00a	3.50a	3.17a	0.73a	1.35a	2.99a
SE±	1.24	1.68	2.43	0.26	0.21	0.26	0.10	0.10	0.16
M*V	*	*	*	*	*	*	Ns	*	*

For each variable, means followed by the same letter in the column are not significantly different by DMRT test

Source: Sakariyawo *et al.* (2013)

Table 15: Effect of AMF inoculation on development parameters, yield component and yield of upland rice varieties

Treatments	Days to 50% flowering	Days to 95% maturity	Panicle length (cm)	Panicle weight (g)	Panicles/m²	Seeds/ panicle	100 seed weight (g)	Yield (kg/ha)
Mycorrhiza (M)								
Without	74.50	0.00b	0.00b	0.00b	0.00b	0.00b	0.00b	0.00b
With	53.5	71.67a	16.39a	2.79a	91.33a	104.8a	2.91a	1586a
SE±	0.66	0.32	0.12	0.02	0.88	2.71	0.04	19.91
Varieties (V)								
NERICA 1	75.33b	42.5b	10.07a	1.74a	51.33c	70.3a	183a	889b
NERICA 2	75.83b	43.17b	9.8ab	1.65bc	55.17b	54.7b	1.82ab	944b
NERICA 3	78.33a	42.17b	9.63ab	1.63c	52.5bc	63.2a	1.77ab c	919b
NERICA 4	75.5b	42.00b	9.58b	1.64c	59.5a	58.2a	1.66bc	1050a
Moroberekan	0.00c	0.00c	0.00c	0.00d	0.00d	0.00c	0.00d	0c
WAB 56 -104	79.00a	45.17a	10.08a	1.71ab	55.5b	68.0a	1.65c	957b
SE±	1.15	0.05	0.20	0.03	1.53	4.70	0.07	34.38
M*V	*	*	*	*	*	*	*	*

For each variable, means followed by the same letter in the column are not significantly different by DMRT test

Source: Sakariyawo *et al.* (2013)

This could be ascribed to the ameliorative effects of AMF on rice (osmoregulatory, osmoprotective) and the soil (nutrient availability). Understanding the potential benefits and mechanisms underlying this symbiotic interaction pave the way for sustainable agricultural practices that address the challenges of drought and contribute to food security in vulnerable areas.

The combination of drought-tolerant NERICA rice varieties and AMF inoculation holds promise for improving crop productivity and resilience in drought-prone regions. Overall, the use of mycorrhizal fungi shows great potential in mitigating the detrimental effects of drought on crop productivity. By improving water uptake, enhancing root development, and enhancing nutrient acquisition, mycorrhizal fungi contribute to increased plant drought tolerance and resilience. Integrating mycorrhizal fungi into agricultural practices is shown to enhance the sustainability and productivity of crops in water-limited environments, contributing to global food security.

7.3.2 ***Studies on the use of mycorrhizal fungi on metallic-nutrients uptake and tolerance***

Mycorrhizal fungi serve as one of the most effective defense approaches against abiotic stresses including bioremediation of heavy metals and promotion of plant tolerance. To provide valuable insights into the potential of AMF as a sustainable and environmentally-friendly approach to enhance the growth and yield of plants in heavy metal-contaminated soil, we conducted numerous studies with *Rhizophagus intraradices*- a model AMF specie, and heavy metals on the uptake of heavy metals (Cu, Pb, and Zn) in soybean plants. The results of the study showed that AMF inoculation had a significant effect on the uptake of heavy metals in soybean plants. Specifically, AMF inoculation reduced the uptake of Cu and Pb in the roots and shoots of soybean plants, while increasing the uptake of Zn in the roots and shoots (Table 16). In addition, the results showed that AMF inoculation increased the plant height, leaf area, root dry weight, shoot dry weight, shoot P content and grain yield of soybean plants in heavy metal-contaminated soil (Table 17). These findings suggest that AMF inoculation help to mitigate the negative effects of heavy metal contamination by reducing the uptake of these toxic metals (Figure 3) and increasing the uptake of essential metals, thus, enhancing the growth and yield of soybean plants in heavy metal-contaminated soil, which have important implications for agriculture and food security (Adeyemi *et al*, 2021).

Table 16: Effect of *Rhizophagus intraradices* on heavy metals (Cu, Pb and Zn) uptake in soybean

Treatment	Content (mg kg^{-1})		
	Root	Shoot	Seed
Control	ND	ND	ND
Cu_{100}	14.6^{f}	12.7^{f}	4.54^{h}
Cu_{300}	25.7^{h}	29.6^{h}	7.64^{g}
Cu (Cu_{100} + Pb_{100} + Zn_{300})	18.4^{f}	28.5^{h}	4.19^{h}
Cu_{100} + AMF	25.8	4.32^{f}	0.92^{f}
Cu_{300} + AMF	64.4^{f}	14.8^{f}	1.34^{f}
Cu (Cu_{100} + Pb_{100} + Zn_{300} + AMF)	33.6^{g}	12.0^{f}	3.50^{h}
Pb_{100}	25.7^{h}	53.5^{f}	9.21^{g}
Pb_{300}	70.1^{f}	110.4^{c}	13.4^{f}
Pb (Cu_{100} + Pb_{100} + Zn_{300})	38.0^{g}	39.4^{g}	12.8^{f}
Pb_{100} + AMF	86.0^{a}	30.7^{h}	7.03^{g}
Pb_{300} + AMF	165.9^{d}	68.8^{a}	12.7^{f}
Pb (Cu_{100} + Pb_{100} + Zn_{300} + AMF)	83.7^{e}	24.4^{h}	13.5^{f}
Zn_{300}	89.6^{e}	92.3^{d}	128.9^{b}
Zn_{600}	166.2^{d}	232.3^{a}	174.3^{a}
Zn (Cu_{100} + Pb_{100} + Zn_{300})	95.6^{a}	93.3^{d}	110.8^{c}
Zn_{300} + AMF	282.2^{b}	73.2^{a}	50.3^{a}
Zn_{600} +AM	441.0^{a}	165.2^{b}	110.5^{c}
Zn (Cu_{100} + Pb_{100} + Zn_{300} + AMF)	193.8^{c}	33.6^{g}	63.0^{d}

Values followed by the same letter in each column are not significantly different from each other (Duncan Multiple range test $P < 0.50$)

Source: Adeyemi *et al.* (2021)

Table 17: Effect of *Rhizophagus intraradices* on growth and grain yield of soybean in heavy metal contaminated soil

Treatment	Plant height (cm)	Leaf area (cm^2)	Root dry weight (g $plant^{-1}$)	Shoot dry weight (g $plant^{-1}$)	Shoot P content (mg g^{-1})	Root P content (mg g^{-1})	Grain yield (g $plant^{-1}$)
Control	71.6d	53.7b	0.29e	5.24e	0.92g	0.67f	6.79b
Control + AMF	93.6a	80.8a	0.39d	9.20a	3.11e	2.32b	13.2e
Cu_{100}	69.9d	23.6f	0.57c	3.74h	1.20f	0.45g	4.12e
Cu_{300}	64.7a	9.4h	0.29e	3.60h	0.75h	0.31h	1.52g
Cu_{100} + AMF	80.7b	42.6c	0.89a	6.91c	3.05a	2.56e	5.98c
Cu_{300} + AMF	75.7c	49.8b	0.43d	5.33e	2.27c	2.12c	3.00f
Pb_{100}	68.0d	21.8f	0.15g	4.43f	0.65h	0.42g	5.19d
Pb_{300}	61.3a	11.0h	0.12g	2.13f	0.45f	0.23f	4.30e
Pb_{100} + AMF	78.5b	35.8d	0.32e	5.33e	2.70b	1.54d	7.49b
Pb_{300} + AMF	67.7d	31.0e	0.21f	4.29g	1.90d	0.76f	4.63d
Zn_{300}	51.7f	32.1e	0.28e	3.69h	0.73h	0.35h	2.23f
Zn_{600}	45.9g	17.1g	0.03h	2.13f	0.35f	0.22f	1.18g
Zn_{300} + AMF	77.6b	49.8h	0.31e	6.05d	1.93d	1.32e	5.98c
Zn_{600} +AM	53.9f	36.1d	0.21f	3.07d	1.54e	1.12e	1.32g
Cu_{100} + Pb_{100} + Zn_{300}	33.0h	28.6e	0.66b	4.90f	0.94g	0.67f	4.17e
Cu_{100} + Pb_{100} + Zn_{300} + AMF	65.7e	30.3e	0.67b	7.13b	2.47e	1.56d	4.96d

Values followed by the same letter in each column are not significantly different from each other (Duncan Multiple range test, $P < 0.05$)

Source: Adeyemi *et al.* (2021)

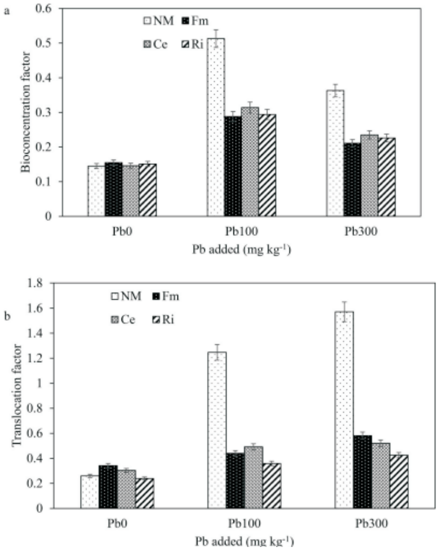

Figure 3: Bioconcentration factor (a) and translocation factor (b) of Pb in soybean grown on Pb-contaminated soils (0, 100, 300 mg Pb kg1). NM, Fm, Ce and Ri indicates control, *Funneliformis mosseae, Claroideoglomus etunicatum and Rhizophagus intraradices*, respectively. Bars are mean values ± SD (n = 3).

Source: Adeyemi *et al.* (2021)

Besides, we found out that AMF inoculation increased the stress tolerance index of soybean plants, indicating that AMF inoculation proved to enhance the ability of soybean plants to tolerate heavy metal stress (Table 18). The findings confirmed the potential of AMF inoculation as a sustainable and environmentally friendly approach to enhance the growth and yield of soybean plants in heavy metal-contaminated soils.

Table 18: Effect of Rhizophagus intraradices on stress tolerance index of soybean in heavy metal - contaminated soil

Treatment	Stress tolerance index (TI)			
	TI_{PH}	TI_{TLA}	TI_{DW}	TI_{GY}
Control	100^{d}	100^{b}	100^{d}	100^{b}
Control + AMF	130.7^{a}	150.5^{a}	175.6^{a}	194.4^{a}
Cu_{100}	97.6^{d}	43.9^{g}	71.4^{f}	60.7^{e}
Cu_{300}	90.4^{e}	17.5^{f}	68.7^{f}	22.4^{h}
Cu_{100} + AMF	112.7^{b}	79.3^{c}	131.9^{b}	88.1^{c}
Cu_{300} + AMF	105.7^{c}	92.7^{b}	101.7^{d}	44.2^{f}
Pb_{100}	95.0^{e}	40.6^{g}	84.5^{a}	76.4^{d}
Pb_{300}	85.6^{g}	20.5^{f}	40.6^{h}	63.3^{e}
Pb_{100} + AMF	109.6^{bc}	66.7^{d}	101.7^{d}	110.3^{b}
Pb_{300} + AMF	94.6^{e}	57.7^{e}	81.9^{e}	68.2^{de}
Zn_{300}	72.2^{h}	59.8^{e}	70.4^{f}	32.8^{g}
Zn_{600}	64.1^{f}	31.8^{h}	40.6^{h}	17.4^{h}
Zn_{300} + AMF	108.4^{bc}	92.7^{b}	115.5^{c}	88.1^{c}
Zn_{600} +AM	75.3^{h}	67.2^{d}	58.6^{g}	19.4^{h}
Cu_{100} + Pb_{100} + Zn_{300}	46.1^{j}	53.3^{f}	93.5^{d}	61.4^{e}
Cu_{100} + Pb_{100} + Zn_{300} + AMF	91.8^{e}	56.4^{f}	136.1^{b}	73.0^{d}

TI_{PH}, TI_{TLA}, TI_{DW}, TI_{GY} indicate stress tolerance indices for plant height, trifoliate leaf area, dry weight and grain yield respectively; values followed by the same letter in each column are not significantly different from each other (Duncan Multiple range test, $p < 0.05$)

Source: Adeyemi *et. al.*, (2021)

7.4 Integrated nutrient management in crop production

7.4.1 Studies on responses of drought tolerant upland 'NERICA' rice to different nutrient supplying treatments in rainforest transitory agroecology

In evaluating the potential of AMF with other nutrient sources, we conducted a study on the effects AMF and different rates of nitrogen (N) and potassium (K) fertilizers on the yield, and the yield attributes of drought tolerant upland 'NERICA' rice cultivars in the rainforest transitory agroecology. The results of the study showed that the different nutrient sources had significant effect on the yield and yield components of upland NERICA rice (Table 19). Specifically, the treatment that received AMF inoculation and 60 kg N/ha + 30 kg K/ha had the highest grain yield, followed by the treatment that received only AMF inoculation. The control treatment had the lowest grain yield. In addition, the different nutrient sources had a significant effect on the panicle length, grain/panicle, 100-grain mass, and grain yield of upland NERICA rice. Specifically, the treatment that received AMF inoculation and 60 kg N/ha + 30 kg K/ha had the longest panicle length, the highest grain/panicle, the highest 100-grain mass, and the highest grain yield. These findings suggest that AMF inoculation and the application of nitrogen and potassium fertilizers have a significant effect on the yield and yield components of upland NERICA rice. These findings are consistent with previous research that has shown the beneficial effects of AMF inoculation and the application of nitrogen and potassium fertilizers on rice yield and its components. AMF has thus proved to enhance nutrient uptake and improve soil fertility, while nitrogen and potassium fertilizers are essential nutrients for plant growth and development (Sakariyawo *et al.* 2017).

Table 19: Effect of nutrient sources on yield and yield components of upland NERICA rice

Treatments	Panicle length (cm)	Grain/panicle	100 grain mass	Grain yield (t/ha)
Nutrient Sources				
AMF	21.46^{c}	80.70^{b}	2.63^{b}	2.51^{a}
AMF + 60kg N + 30kg K	25.92^{a}	106.60^{a}	3.07^{a}	2.54^{a}
60kg N + 30kg K	23.82^{b}	81.30^{b}	3.07^{a}	2.41^{a}
CONTROL	17.48^{d}	91.20^{b}	2.69^{b}	1.53^{b}
Varieties	22.64^{ab}	102.9^{a}	3.07a	2.89^{a}
NERICA 1	24.09^{a}	98.40^{ab}	2.72^{ab}	2.90^{a}
NERICA 2	22.66^{ab}	92.30^{abc}	2.83^{ab}	2.53^{b}
NERICA 3	19.66c	86.40^{bcd}	2.83^{ab}	2.19^{c}
NERICA 4	23.13^{a}	85.00^{cd}	2.83^{ab}	1.68^{d}
WAB 56-104	20.83^{bc}	74.70^{d}	2.50^{b}	1.22^{e}
Moroberekan				
Varieties Nutrient Sources	**	**	NS	NS

Means with the same alphabets are nonsignificantly different using Duncan Multiple Range Test (DMRT) at 5% level of significant. *means significant at 5% probability level, **means significant at 1% probability level

Source: Sakariyawo *et al.* (2017)

7.4.2 Studies on grain yield components of selected upland rice grown in valley bottom soil under rates of foliar Ortho- Silicate Acid (OSA) fertilizer

We explored the effects of foliar OSA fertilizer on the grain yield components of selected upland rice cultivars grown in valley-bottom soil. The study consisted of four rates of OSA fertilizer (0, 250, 500, and 750 ml ha^{-1}), five upland rice cultivars, and three replications. We observed that the recommended rate of OSA fertilizer for upland rice cultivars grown in valley bottom soil was 500 ml ha^{-1}. The application of OSA fertilizer increased grain weight per plant, and the least percentage number of fertile spikelets and grain weight per plant were obtained with the control (Table 20).

Table 20: Effect of rates of Ortho -Silicate Acid fertilizer and cultivar on grain weight and its attributes of selected upland rice cultivar

Sources of variation	Levels of variation (ml ha^{-1})	Total number panicle $plant^{-1}$ (TNPP)	Total weight of panicle $plant^{-1}$ (TWPP)	Length of panicle $plant^{-1}$ (LPP)	Number of grains branch $plant^{-1}$ (NGBPP)	Total number of spikelet panicle $plant^{-1}$ (TNSPP)	% number fertile spikelet panicle $plant^{-1}$ (%NFSPP)	One thousand grain weight 1000 GW (g)	Grain weight $plant^{-1}$ GWP (g)
OSA	0	3.20^{a}	61.8^{a}	21.85^{a}	9.07^{a}	318^{a}	48.80^{a}	26.0^{a}	4.67^{a}
Fertilizer	250	3.53^{a}	7.64^{a}	22.98^{a}	9.03^{a}	356^{a}	69.30^{a}	27.7^{a}	7.58a
Rates (R)	500	3.73^{a}	9.06^{a}	23.12^{a}	9.46^{a}	387^{a}	71.30^{a}	26.1^{a}	8.51a
(ml ha^{-1})	750	3.80^{a}	8.47^{a}	22.49^{a}	8.96^{a}	410^{a}	66.70^{a}	25.2^{a}	7.17^{a}
	LSD (0.05)	0.18^{a}	2.50	1.69	0.20	2.79	0.63^{a}	2.5^{a}	2.21
	Significance	^{ns}	ns	Ns	Ns	ns	**	ns	**
Cultivars (C)	NERICA 1	$^{3.92a}$	7.60^{a}	20.69^{a}	11.02^{a}	472^{a}	58.30a	21.8^{a}	6.62^{ab}
	NERICA 4	3.83^{a}	9.47^{a}	22.58^{b}	9.25^{b}	387^{ab}	63.40^{b}	29.1^{a}	8.52^{a}
	NERICA 7	3.75^{a}	8.68^{a}	23.31^{b}	9.45^{b}	399^{ab}	66.60^{ab}	26.9^{ab}	7.42^{a}
	Moroberekan	2.50^{a}	9.05^{a}	26.74^{a}	9.46^{a}	3.37^{a}	78.60	28.5^{a}	7.54^{a}
	Ofada	3.83^{a}	4.39^{a}	19.74^{a}	6.48^{a}	245	53.70	24.8^{b}	4.81^{b}
	LSD	0.20	2.80	1.89	0.22	3.12	0.70	2.8	2.48
	Significance	**	**	**	**	**	**	**	*
R x C		ns	ns	Ns	Ns	ns	ns	ns	Ns
CV (%)		12.1	43.2	10.1	8.8	20.1	10.7	13.1	43.0

**, * = significant at 1% and 5% level of probability; ns = non-significant; LSD = Least significant difference; LSD values with superscript "t" are obtained from transformed data

Source: Olagunju, *et al.* (2020)

The study also found that significant differences in grain weight and its components were observed among the cultivars, with Ofada variety maintaining the lowest values for all. We concluded that further improvement in yield of upland rice grown on valley bottom soil under foliarly applied silicon should focus on percentage number of fertile spikelets per panicle plant-1, total weight of panicle plant-1, and length of panicle plant-1. The study also highlights the importance of silicon in the growth and yield of upland rice, as foliar applied silicon improved the yield components of upland rice cultivars grown in valley-bottom soil (Olagunju *et al.* 2020).

7.4.3 ***Studies on rates of inorganic nitrogen fertilizer and calcium carbide on nitrogen harvest index, partial factor productivity, agronomic efficiency, physiological efficiency and apparent recovery efficiency***

In optimizing the rates of N fertilizer application, we conducted a study in 2016 and 2017 on the effect of different rates of inorganic nitrogen fertilizer and calcium carbide (CaC_2) on the nitrogen harvest index, partial factor productivity, agronomic efficiency, physiological efficiency, and apparent recovery efficiency of two maize varieties in late 2016 and early 2017. The CaC_2 was used as nitrification inhibitors. The findings of the study showed that the different rates of inorganic nitrogen fertilizer and calcium carbide had a significant effect on the nitrogen harvest index, partial factor productivity, agronomic efficiency, physiological efficiency, and apparent recovery efficiency of the two maize varieties (Table 21). The treatment that received the highest rate of inorganic nitrogen fertilizer (240 kg N/ha) and calcium carbide (4 kg/ha) had the highest nitrogen harvest index, partial factor productivity, agronomic efficiency, physiological efficiency, and apparent recovery efficiency. In addition, the different rates of inorganic nitrogen fertilizer and calcium carbide had a significant effect on the total nitrogen uptake of the two maize varieties. Specifically, the treatment that received the highest rate of inorganic nitrogen fertilizer (240 kg N/ha) and calcium carbide (4 kg/ha) had the highest total nitrogen uptake.

These findings concluded that the application of inorganic nitrogen fertilizer and calcium carbide can have a significant effect on the nitrogen use efficiency and yield of maize (Sakariyawo *et al.* 2020). Inorganic nitrogen fertilizer is an essential nutrient for plant growth and development, while calcium carbide can help to improve soil fertility and enhance nitrogen use efficiency.

Table 21: Effect of rates of inorganic nitrogen fertilizer and calcium carbide on nitrogen harvest index, partial factor productivity, agronomic efficiency, physiological efficiency and apparent recovery efficiency of two maize varieties in late 2016 and early 2017

Treatments	Total n uptake (kg)		Nitrogen harvest index		Partial factor productivity (kg kg^{-1})		Agronomic efficiency (kg kg^{-1})		Physiological efficiency (kg kg^{-1})		Apparent recovery efficiency (kg kg^{-1})	
	Late 2016	Early 2017	Late 2016	Early 2017	Late 2016	Early 2017	Late 2016	Early 2017	Late 2016	Early 2017	Late 2016	Early 2017
Variety												
SUWAN 1	104.6	138.7	0.09	0.12	39.9	49.1	16.5	20.1	13.4	11.9	1.16	1.54
OBA SUPER II	90.1	136.0	0.08	0.12	40.5	56.7	17.1	27.7	17.1	17.6	1.00	1.51
Lsd	11.2*	ns	ns	ns	Ns	5.66*	Ns	5.66*	2.72*	1.55*	0.12*	ns
Nitrogen level (kg/ha)												
0	66.6	106.3	0.05	0.08	44.2	61.7	20.8	32.7	16.5	17.5	1.26	1.87
60	113.1	168.2	0.09	0.14	43.3	50.7	19.9	21.7	15.7	13.6	1.25	1.53
90	112.3	137.6	0.12	0.15	33.1	46.3	9.75	17.2	13.5	13.1	0.74	1.18
Lsd	11.0*	10.0*	0.01*	0.02*	4.05*	7.81*	4.04*	7.81*	Ns	2.73*	0.12*	0.26*
CaC_2 (kg/ha)												
0	104.2	146.0	0.08	0.11	41.3	53.6	16.7	24.5	14.4	14.6	1.16	1.62
30	95.9	136.0	0.09	0.11	40.1	53.5	18.0	24.5	16.6	15.6	1.07	1.51
60	92.0	130.1	0.10	0.11	39.2	51.6	15.8	22.6	14.8	14.1	1.02	1.45
Lsd	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
V x N	ns	12.1*	ns	0.02*	ns	9.28*	ns	9.28*	ns	ns	ns	0.30*
V x C	ns	Ns	ns	Ns	ns	ns	ns	ns	3.52*	ns	ns	Ns
N x C	20.9*	16.4*	0.02*	0.03*	ns	12.0*	ns	12.0*	4.54*	4.74*	0.23*	0.37*
V x N x C	28.9*	Ns	Ns	Ns	ns	ns	ns	ns	ns	6.45*	0.32*	ns

WAP, Weeks after plantin g; LSD, Least significant difference; ns, not significant. Significant at 5% level probability. Significant at 1% level of probability

Source: Sakariyawo *et al.* 2020

8.0 FUTURE RESEARCH OUTLOOK AND ENVIRONMENTAL CONCERNS

As a researcher in the field of crop nutrition, I am inspired by the potential of mycorrhizal-based nanofertilizers to revolutionize the way crops are nourished. By combining the power of mycorrhizal symbiosis and nanotechnology, these innovative fertilizers hold the key to unlocking unprecedented advancements in sustainable agriculture. Imagine a future where we can enhance nutrient-capturing capabilities, improve nutrient uptake efficiency, and promote sustained nutrient release through the integration of mycorrhizal fungi with nanomaterials. These fertilizers have the potential to provide controlled and targeted nutrient release, minimize waste and reduce environmental pollution. Furthermore, they hold the promise of increasing crop productivity, bolstering stress tolerance, and fortifying disease resistance by optimizing plant-fungus interactions and nutrient availability. The fusion of mycorrhizal symbiosis and nanotechnology offers us a pathway towards sustainable crop nutrition with a reduced ecological footprint.

However, as we embark on this exciting journey, we must also be mindful of the environmental concerns associated with these novel fertilizers. We must undertake rigorous investigations to determine the fate and ecotoxicity of nanoparticles, as well as understand their potential impact on soil microorganisms, beneficial insects, and other non-target organisms. Additionally, assessing the mobility and potential bioaccumulation of nanoparticles is crucial for evaluating their long-term effects on ecosystems and human health. It is our responsibility to establish robust regulatory frameworks and conduct comprehensive risk assessments, guiding the production, distribution, and responsible application of mycorrhizal-based nanofertilizers.

Looking ahead, our future research endeavours shall focus on optimizing the formulation of these fertilizers. We shall consider various factors, including nanoparticle type, size, concentration, and their compatibility with different mycorrhizal fungi and crops. Comprehensive environmental impact assessments, spanning from laboratory studies to field trials and ecosystem-level analyses, shall be conducted to evaluate the potential ecological consequences of these fertilizers. Furthermore, we must address knowledge gaps surrounding the intricate mechanisms of interaction between nanomaterials, mycorrhizal fungi, and plants. By deepening our understanding of both the benefits and risks associated with mycorrhizal-based nanofertilizers, we can pave the way for their responsible implementation, contributing to sustainable agriculture, global food security, and a diminished ecological footprint.

In conclusion, the journey before us is filled with boundless potential and endless discoveries. Together, let us embark on this path of research, innovation, and responsibility, as we strive to shape a future where mycorrhizal-based nanofertilizers propel us towards sustainable agriculture and a greener world.

9.0 HUMAN CAPITAL DEVELOPMENT AND UNIVERSITY SERVICES

Precisely on the 26th September, 2023, I had spent 29 years in the services of this university. I joined as an Assistant Lecturer and about a year later I was upgraded to Lecturer II. At an average of four undergraduate students per year, 116 of them would have passed through me by now. I have mentored more than 24 students at Masters Degree level. I have also contributed to training of more than 25 PhD students as a supporting supervisor while I was the major supervisor for eight (8) of them.

I have been blessed with very great, brilliant and hard working postgraduate students. Prominent among them are, Prof. Akeem Ajiboye, Drs Olagunju Solomon, Adeyemi Nurudeen, Hafiz Eruaga, Mr. Hafeez Mogaji, Mbet Akan, Miss Ijiola Mary, Doyin

Jenfa, Omotayo Ajenifuja, Adegoke Idowu. All of them are prominent in their chosen paths.

I have contributed my quota towards the success of every administration of the University starting from Prof Olorunimbe Adedipe to Prof F. K. Salako. I served as a prominent member of the then Management Committee on Transportation (MANCOT) and later as the Chairman till 2007. I was the Acting Head, Department of Plant Physiology and Crop Production in 2001 and moved to become the Deputy Dean, Students Affairs with Prof C. F. I. Onwuka and C. O. N. Ikeobi as Deans in succession. I was again appointed as Acting Head, Department of Plant Physiology and Crop Production for another four (4) years in 2009. In 2014, I was nominated and accepted by the College Board as the Deputy Dean of College of Plant Science and Crop Production (COLPLANT) under Prof J. G. Bodunde. In 2015, I became the substantive Dean and spent two terms of 3 years each. During my term as the Dean, I became the Chairman, Committee of Deans and Directors (CODAD), and a member of Council of the University. I was Secretary, Committee of Deans of Agriculture in Nigeria (ADAN), and the Chairman, Admission Committee of the University. I have served on many committees outside the University including the Committee on the Seamless transfer of Universities of Agriculture to the Ministry of Agriculture among others. I have also been involved in the assessment of candidates for promotion to Professorial Cadre in Nigerian Universities and other institutions outside the shores of Nigeria.

10.0 CONCLUSIONS

Farming is not simply a traditional practice; it encompasses a dynamic interplay between plants and their environment in the pursuit of sustainable food production. At the heart of this intricate web lies the critical role of crop nutrition, which is central to addressing pressing challenges such as food security, environmental sustainability, and human health. There is an urgent need for innovative strategies and transformative change in the

realm of crop nutrition. Modern agricultural practices face significant issues, including soil degradation, nutrient depletion, and the detrimental effects of chemical fertilizers on the environment. To overcome these challenges, it is imperative to adopt sustainable cultivation techniques that prioritize soil health and balanced nutrient replenishment. Exploring diverse approaches such as organic farming, precision agriculture, and integrated nutrient management holds the potential to revolutionize crop nutrition. By adopting these sustainable practices, we can promote the replenishment of vital nutrients, reduce environmental impact and ensure the long-term viability of agriculture. This calls for collaborative efforts between crop nutritionists, agronomists, environmental scientists, and policy-makers to develop holistic solutions that integrate scientific knowledge, traditional wisdom, and technological advancements.
In essence, this discourse highlights the transformative power of understanding and implementing innovative strategies for enhanced crop nutrition. By embracing sustainable practices, harnessing scientific advancements and prioritizing the well-being of our soils, we can lay the foundation for a resilient and nourishing agricultural system. This endeavour is crucial to secure the provider of food for present and future generations does not starve and is able to ensure food security, preserve the environment and promote the holistic well-being of humanity.

1.0 RECOMMENDATIONS

1. Researches and farmers should focus on sustainable crop nutrition practices such as organic farming, biofertilization, precision agriculture, and integrated nutrient management to increase crop yield and quality, while minimizing environmental impact.
2. Government agencies and agro-allied industries should support research initiatives focused on crop nutrition, soil health, and sustainable agriculture.
3. Nigerians should consider heavy investment in agriculture as

it is done in other sectors of the economy like oil and gas, real estate etc.

4. Federal Universities of Agriculture should emphasize on innovative nutrient management techniques in agricultural training to elicit the interest of students and farmers
5. National Agricultural Research Institutes (NARIs) should promote recent development and sustainable innovations in their research activities to educate and empower farmers. They should also educate consumers about the importance of nutrient-rich foods and the role of sustainable crop production in ensuring nutritional security.

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My father, Pa Salawu Oyewale Atayese, exited this wonderful world before I could say, 'e kaaro baami' at the age of less than three. I am not even sure I could recognize him. At the time he left, we were three naughty boys and a gentle girl with 'Maami' and the last born came about three months after his death. God had been so wonderful in our lives that he spared our mother's life till this moment. Though, very aged but still very active until six months ago when she fell as usual of old bones. She sacrificed every comfort of life to keep us going. I recall telling her after primary school that I wanted to further my education, “You will read and get to the peak of your chosen career”, she replied. I wondered within myself how she intended to achieve that. Today, I need not wonder any longer, judging from today's testimony. At this stage in my life, I have concluded that mothers' prayers for children are an important tool for survival and excellence.

My brothers; Yunus Atayese, Mudathir Oladapo Atayese (my sparring partner), late Sulu Oyejide Atayese, and the only woman among us Adijat Morolake Laniyan who was the foster mother for

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I dedicate the two stanzas below to you my love from a song by Withney Huston titled

" My love is your love".

If tomorrow is judgment day
And I'm standing on the front line
And the Lord asks me what I did with my life
I will say, I spent it with you

If I wake up in World War III (World War III)
I see destruction and poverty
And I feel like I want to go home
It's okay if you're coming with me
As the years pass us by
We stay young through each other's eyes
And no matter how old we get
It's okay as long as I got you baby

If I should die this very day
Don't cry (don't cry), 'cause on Earth we weren't meant to stay
And no matter what the people say don't matter)
I'll be waiting for you after the judgment day

'Cause your love is my love
And my love is your love
It would take an eternity to break us
And the chains of Amistad couldn't hold us

Whitney Huston (1963 -2012)

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