



Strategic research in the domain of secondary nutrients, micronutrients, liming and 4R stewardship in sub-Saharan Africa: Review

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ABSTRACT

Low levels of secondary and micronutrients, and soil acidity strongly challenge the attainment of two critical pillars of Climate Smart Agriculture (CSA); 1) secured food through increased productivity and (2) increased resilience to adapt to climate change. Despite this soil fertility trend, empirical and review studies on secondary and micronutrients, and soil acidity remain scanty few. This review is thus timely and imperative as it aims to; 1) piece together different strategic empirical research in the domain of secondary nutrients, micro nutrients, liming and 4R stewardship, and 2) give a snapshot of challenges in soil fertility research in sub-Saharan Africa. The review adopted multi-engine search including; Science Direct, Google Scholar, and Research Gate. Key findings of the review are; i) response of yield to application of secondary and micro-nutrients denotes hidden hunger of these nutrients; ii) Combination of lime and fertilizers has a better effect on yield than sole applications; iii) scarce lime markets in areas with profound acidic soils, iv) developing lime supply chain in areas with no assisting supply chains is expensive, and v) lack of robust policy, legal framework and political goodwill on fertility input markets. We propose a responsive soil-specific balanced nutrition framework supported by robust policy and legal frameworks in fertilizer and lime markets to address soil acidity, macro, micro and secondary nutrients. Next generation soil fertility management researchers and other stakeholders, supported by high-end assessment technologies, should conduct more secondary and micro-nutrient-specific empirical studies that involve different forms and rates to validate the framework on different soil types.

1. Introduction

Soil fertility status for most major nutrients at regional and national levels are negative and vary considerably even within fields of the same farm leading to low agricultural productivity (Chianu et al., 2012; Vanlauwe et al., 2006). The widespread negative nutrient imbalances which are common in sub-Saharan Africa (SSA) are as a result of traditional farming practices that either under- or fail to replenish soil fertility (Otieno et al., 2021, 2023). This is because the uptake of soil fertility amendments like mineral fertilizers, lime and organic inputs are hindered by socio-economic attributes of the farming population and technology characteristics (Mugwe et al., 2009). The problem is further compounded by; high cost and physical inaccessibility of soil fertility amendments, farmers' risk averseness and less attention to status of soil micro- and secondary nutrients (Mucheru-Muna et al., 2021).

Soil micronutrients are essentially required by plants in relatively small amounts and include; boron (B), chloride (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni) and zinc (Zn) (Shukla et al., 2015). Secondary nutrients are crucial elements needed by plants in comparatively larger amounts than micro but lesser than macro-nutrients and include; Magnesium (Mg), calcium (Ca), and sulfur (S) (Grzebisz et al., 2023). Mineral rocks are the natural sources of both micro and secondary nutrients, which are involved in critical biochemical functions in plants (Table 1).

Empirical soil fertility management studies are macro nutrient-based with little to no attention on micro- and secondary nutrients and liming (Kihara et al., 2017, 2020). Few studies that involved commonly limiting micro and secondary nutrients in SSA are shown in Table 2. Resultantly, deficiencies of these nutrients are widespread in SSA (Geng et al., 2021; Vanlauwe et al., 2015). The deficiency symptoms are often

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less visible and harder to reliably evaluate compared to their counterparts, macronutrients, thus, their omission in most soil fertilization programs (Singh et al., 2018). There is need for on-site trials that replenish the nutrients through application of fertilizers to evaluate their deficiencies. Improving and sustaining micronutrient concentrations in feed and food is critical in livestock and human health yet few studies have assessed their improvement in soils (Miner et al., 2018).

Low soil micronutrients like Cu, Zn, and Mn, and secondary nutrients; Mg, Ca and S have been reported in agricultural fields under low input cropping systems (Kihara et al., 2020; Kopittke et al., 2017; Shambhavi et al., 2018). Zinc has been described as the fourth most yield-limiting crop nutrient after N, P and K, because it is a constituent element of chlorophyll and its deficiency impairs photosynthesis hence lowering crop yields. Shukla and Anshumali (2018) found low mobility of Cu, Zn and Fe in rainfed rice farming in semi-arid ecosystem. Additionally, Doncato and Costa (2021) intimated that micronutrient demand by plants in salt-affected soils remain a gray area. Micronutrient contents also tend to decrease with increasing depth, and vary according to land use, soil type, site, and element (Sátiro et al., 2021). On the other hand, a combination of complex factors are contributing to the increasing secondary nutrients deficiencies in various agricultural farms in SSA; i) use of inorganic fertilizers with little or on secondary nutrients, ii) continues mining by high yielding crops, and iii) cultivating soils that inherently contain low secondary nutrient reserves (Shambhavi et al., 2018).

Soil acidity affects over 30% of the dry land and a crucial limiting factor in agricultural productivity around the world (Gurmessu, 2021). Soil acidity is the most significant source of low yield for a lot of crops and it limits crop growth, yield as well as soil productivity in highly

weathered soils due to deficiency of essential nutrient elements. Acidity contributes immensely to the over 65% of degraded land in Africa and reduces annual agricultural gross domestic product by 3% (Agegnehu et al., 2021). Agegnehu et al. (2021), report that soil acidity is still expanding both in area and severity in SSA affecting majority of East, Central, West, and southern Africa. Acidity in most of the agricultural land in SSA are classified as 'strongly acidic' (Scandinavica et al., 2017). The current soil acidity levels partially explain the low yield of leading staple crops like maize at less than 2 t ha⁻¹ relative to 5.5 and 8.0 t ha⁻¹ in Asia and America, respectively (FAO, 2019). Management of soil acidity is becoming one of the major strategies of addressing food security in SSA (Agegnehu et al., 2021).

The available literature is short of comprehensive strategies to improve soil micro-and secondary nutrients despite their prominence in increasing agricultural production and deficiency symptoms being recorded in agricultural fields globally (Kumar and Babel, 2011). The problem of micronutrient deficiency was manifested in the rice yield response to micronutrient application in Tanzania (Senthilkumar et al., 2021). It is estimated that 49, 31, 15, 14, 10 and 3% of agricultural soils worldwide are deficient in Zn, B, Mo, Cu, Mn and Fe, respectively (Alloway, 2008). Lack of Zn alone is estimated to be responsible for almost 50% of cultivated land producing suboptimal crop growth universally (Singh et al., 2018). This therefore, strongly underscored the need for this manuscript that aimed to piece together different strategic empirical research in the domain of secondary nutrients, micro nutrients, liming and '4R' stewardship. We strongly believe that balanced plant nutrition (BPN) is the most viable strategy to curb the declining soil fertility and raise agricultural productivity to its optimal potential. Christened '4R' the approach is at the core of BPN and entails; i) right

Table 1
Secondary and micronutrients, major roles in plant nutrition and some mineral sources of the nutrients.

Nutrient	Major roles in plants	Mineral source	Reference
Magnesium	Synthesis, production and transportation of chlorophyll, protein synthesis, photo-assimilates utilization, and enzyme activation.	Magnesite (MgCO ₃), dolomite (MgCO ₃ .CaCO ₃) and carnallite (KMgCl ₃ .6(H ₂ O))	Cai et al. (2021), Scipin et al. (2019), and Štofejšová et al. (2021)
Calcium	a counter-cation for anions also required for structural roles in the cell wall and membranes (White and Broadley, 2003).	Anhydrite (calcium sulfate; CaSO ₄), gypsum (hydrated calcium sulfate; CaSO ₄ .2H ₂ O), aragonite or calcite (calcium carbonate; CaCO ₃), and dolomite (MgCO ₃ .CaCO ₃)	Griffith et al. (2020) and Kang et al. (2019)
Sulfur	Formation of chlorophyll, nodulation, amino acids, proteins, and oils and activates some enzymes (Kopriva et al., 2019).	Anhydrite (calcium sulfate; CaSO ₄), barite (barium sulfate; BaSO ₄), chalcocite (copper sulfide; Cu ₂ S), chalcopyrite (CuFeS ₂), cinnabar (mercury sulfide; HgS), galena (lead sulfide; PbS), kieserite (magnesium sulfate; MgSO ₄ .H ₂ O), gypsum (CaSO ₄ .2H ₂ O), sphalerite (zinc sulfide; (Zn,Fe)S), and stibnite (antimony sulfide; Sb ₂ S ₃)	Ding et al. (2021) and Sun et al. (2020)
Boron	Development of fruits, seeds, cell wall, and hormones. Also transports sugars (Ali et al., 2020).	Colemanite (Ca ₂ B ₆ O ₁₁ .5H ₂ O), ulexite (NaCaB ₅ O ₆ (OH) ₆ .5H ₂ O), tincal (-10H ₂ O), and kernite (Na ₂ B ₄ O ₇ .4H ₂ O)	Kistler and Helvacı (1994) and Trumbull and Slack (2018)
Chloride	Promotes cell osmoregulation, turgor-driven processes, elongation of leaf cell, and reduce stomatal conductance (Rosales et al., 2020).	Sodalite (Na[AlSi ₃ O ₇]Cl) and apatite (Ca(PO) ₃ (Cl,F,OH))	Jassim and Al-Badri (2019)
Copper	Important in several enzymatic activities in plants. Also crucial in chlorophyll and seed production (Yruela, 2005).	Azurite (Cu ₃ (CO ₃) ₂), malachite (Cu ₂ CO ₃ (OH) ₂), chalcocite (Cu ₂ S), chalcopyrite (CuFeS ₂) and bornite (Cu ₅ FeS ₄).	Tabelin et al. (2018) and Wilson et al. (2016)
Iron	Synthesizes chlorophyll, and important in the maintenance of chloroplast structure and its function (Lucena and Hernandez-Apaolaza, 2017).	Goethite ((Fe(OH)O)), hematite (ferric oxide; Fe ₂ O ₃), lepidocrocite (FeO(OH)), magnetite (iron oxide; Fe ₃ O ₄) and siderite (iron carbonate; FeCO ₃).	Schwertmann and Fitzpatrick (1992)
Manganese	Plays crucial roles in N assimilation, photosynthesis, and respiration. It is also involved in germination and growth of pollen and pollen tubes in addition to promoting elongation of root cells. The nutrient helps plants to resist root pathogens and catalyzes hydrolysis in photosystem II (Alejandro et al., 2020).	Pyrolusite (alpha-manganese dioxide; MnO ₂) and romanecchite ((Ba,H ₂ O) ₂ (Mn ⁴⁺ ,Mn ³⁺) ₅ O ₁₀).	Roy (1968)
Molybdenum	Important in the symbiotic nitrogen fixation. It also transforms nitrogen into amino acids (Muhammad et al., 2020).	Biotite (K(Mg,Fe) ₃ AlSi ₃ O ₁₀ (F,OH)2), amphibole (X ₇ Si ₈ O ₂₂ (OH) ²⁻), pyroxene (XYSi ₂ O ₆), magnetite (Fe ²⁺ Fe ³⁺ 2O ₄) and ilmenite ((Fe, Ti) ₂ O ₃).	Greaney et al. (2018)
Nickel	A cofactor that enables urease to catalyze conversion of urea into ammonium (Muhammad et al., 2020).	Garnierite ((NiMg) ₆ Si ₄ O ₁₀ (OH) ₈) and nickeliferous limonite ((Fe, Ni)O(OH)-nH ₂ O)	(British Geological Survey (2008)
Zinc	A crucial structural, enzymatic, and regulatory component of enzymes and proteins. It promotes formation of carbohydrates and chlorophyll, auxins (aids in the stem elongation and growth regulation). It also converts starches to sugars and makes the plant withstand cold temperatures (Stanton et al., 2022).	Sphalerite (zinc sulfide; (Zn,Fe)S), smithsonite (zinc carbonate; ZnCO ₃), hemimorphite (zinc silicate; Zn ₄ (Si ₂ O ₇)(OH) ₂ .H ₂ O), zincite (zinc oxide; (Zn,Mn)O), willemite (Zn ₂ SiO ₄) and hydrozincite (Zn ₅ (CO ₃) ₂ (OH) ₆).	Mudd et al. (2017)

Table 2
Sources of secondary and micronutrients and proposed application rates in empirical studies.

Micro/secondary nutrient	Form/source	Crop(s)	Rate	Reference
Zn	Foliar (water soluble Zn 8.0% w/w)	Beans	200 g ha ⁻¹	Yeboah et al. (2021).
Magnesium	magnesium sulfate monohydrate (MgSO ₄ ·H ₂ O, 16.0% Mg)	Rapeseed plants	45 kgm Mg ha ⁻¹	Cole et al. (2016) and Geng et al. (2021).
		Radish	0.10 g Mg kg ⁻¹ soil	Yousaf et al. (2021).
	magnesium chloride (MgCl ₂ ·6H ₂ O)	tomato	*	Cole et al. (2016).
Calcium	Magnesium ammonium phosphate Foliar (MgO water soluble 5.0% w/w)	Beans	224 g ha ⁻¹	Yeboah et al. (2021).
	Calcium peroxide (CaO ₂)	Rice	0, 5, 10, and 20 g CaO ₂ kg ⁻¹	Syu et al. (2020).
	• Calcium-chloride • Calcium-based fluid mixture with a bio-stimulant	Tomato	• 10.050 g l ⁻¹ • 5 mL l ⁻¹	Bertoldo et al. (2023).
	Calcium nitrate tetrahydrate (Ca(NO ₃) ₂ ·4H ₂ O)	Runner bean	1000 mg l ⁻¹	Skórzyńska-Polit et al. (1998).
Calcium oxide nanoparticles (CaONPs)	Canola	25, 50, 75, and 100 ppm	Mazhar et al. (2022).	

fertilizer type, ii) right application time, iii) right application rate, and iv) right fertilizer placement. Consolidating findings of the previous studies that involved the 4R's will showcase and improve the understanding of this novel approach.

2. Literature search and management

We conducted in-depth and systematic literature search through; ScienceDirect (<https://www.sciencedirect.com>), Google Scholar (<https://scholar.google.com>), and ResearchGate (<https://www.researchgate.net>). The research involved literature published from 2010 to 2022. Soil acidity, secondary and micro-nutrient challenges have been prominent in the past decade spanning from the year 2010 (Agegnehu et al., 2021; Popkin et al., 2011). The scope of the review was to capture the most recent studies in the realm of soil acidity, secondary and micro-nutrient, and 4Rs.

The literature search was conducted using key words like agricultural productivity, soil micro-nutrient, soil secondary nutrients, lime, liming, liming materials, fertilizer placement, fertilizer application rates, fertilizer application timing, types of fertilizers, modern soil fertility management technologies, soil acidity, and balanced soil/plant nutrition (Fig. 1). The literature materials obtained and involved in this study were empirical trials carried out in SSA. A total of 1247, 1757, 631, and 196 articles relating to soil micronutrients, secondary nutrients, soil acidity, and 4R stewardship were recovered in the initial search. However, 74, 30, 21, and 20 published articles that provided empirical evidence of state-of-the-art management of soil micro and secondary nutrients, acidity and 4R stewardship were retained and reviewed. The authors critically assessed the objectives of the journal articles, their methodology, key findings and recommendations. The main aim of the assessment was to evaluate the relevance of the literature materials in addressing objectives of the current study. The data and information obtained were synthesized and used to discuss key aspects of in this study.

3. Literature synthesis and discussion

3.1. Strategic research in the domain of micronutrients

Micro nutrients deficiencies in agricultural soils are fast becoming the primary constraints to soil efficiency, stability, sustainability and a major contributor to widespread human malnutrition (Popkin et al., 2011). The effect of deficiencies of these nutrients also spills over to the livestock production (Singh et al., 2018). These nutrients were available and adequate in the past in tropical soils as a function of chronosequence

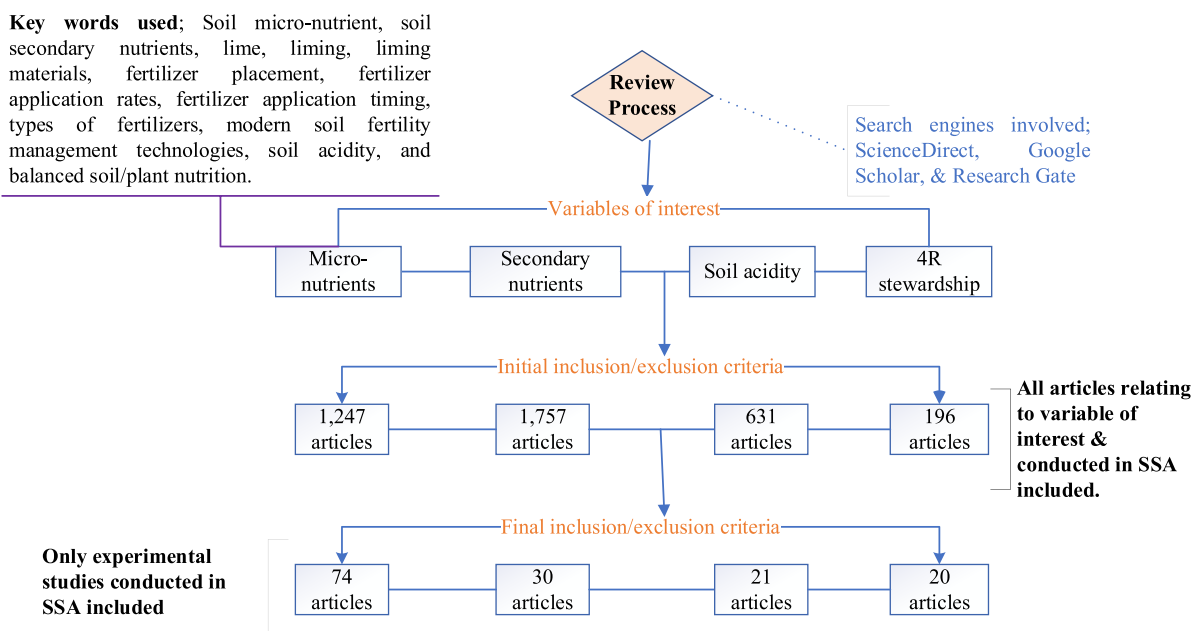


Fig. 1. Literature search process involving number of published articles recovered and retained.

rather than external supplementation (Kamarudin et al., 2020). However, their deficiency symptoms are becoming more pronounced due to continuous cultivation and mining of micronutrients through crop harvesting without equivalent replenishment, coupled with effect of climate change (Shukla et al., 2018). It was until recently that symptoms of micronutrients were observed in crops (Kihara et al., 2020). This has been a game changer in fertilizer formulation and fertilization programs. The urgency of including these nutrients in fertilization programs cannot be overemphasized in the era of climate change and development of high yielding cultivars. These nutrients play crucial role in enhancing crops resilience to climate change and sustain enhanced food production (Fig. 2). Some state-of-the-art strategic empirical studies in the management of micronutrients are discussed here.

3.1.1. Use of biosurfactant

Microbial metabolite is becoming an area of soil fertility interest as it offers a sustainable pathway to improving agricultural productivity. Biosurfactant is multifunctional microbial metabolite with ability to sustainably increase nutrient availability (Baccile, 2023; Kleinen, 2023). It is a surfactant produced extracellularly by numerous microbes in relatively larger quantities (Thirumurugan et al., 2023). Studies have considered the potentials of biosurfactants from different isolates to improve soil fertility and promote crop growth (Das et al., 2021).

The application of bacterial strains with ability to produce biosurfactants is a relatively modern approach to increasing micronutrients availability to plants through dissolution of micro-nutrients and metals (Olorunfemi and Lolodi, 2011; Plociniczak et al., 2011). Whether the micro nutrients become available to plants from the soil depends on solubility and mobilization. Micro-nutrients from various sources have to be solubilized to allow uptake. Sources of the micro-nutrients can be categorized as; i) natural sources (e.g., geologic parent material, volcanoes, forest and prairie fires), ii) agricultural sources, usually of manure origin (e.g., green manure, compost, spent mushroom media, crop residues, wash water, silage juice, farmyard manure, biomass transfer and spent supplement solutions), iii) industrial sources like sewage wastes, and iv) domestic effluents.

Biosurfactants can improve nutrient status, promote soil wettability, and obtain a relatively even distribution of complex nutrients. Scholars have recently assessed effect of biosurfactants on soil flushing efficiency, bioremediation and antimicrobial activities (Ahmad et al., 2018; Singh

and Rathore, 2019; Singh et al., 2018; Vaishnavi et al., 2021; Zohra et al., 2014). It has been shown that the metabolite has great potential of mobilizing and solubilizing soil nutrients and making them available for plant uptake by forming metal-biosurfactant complexes and releasing the micro-nutrients (Singh et al., 2020).

A review by Singh et al. (2018) gives more insights on the applicability of biosurfactants on specificity for Zn, Mn and Cu and bioremediation of heavy metals from soils (Mishra et al., 2021). Improvement in microbial population dynamics under crude biosurfactants has been reported (Das et al., 2021). Low concentrations of textile effluent are alternative source of soil micro-nutrients. Soils treated with low concentrations of textile and biosurfactant (lipopeptide) showed increased micronutrients, higher microbial population and enzymatic activities (Singh et al., 2020).

3.1.2. Use of microalgae and cyanobacteria

Microalgae and cyanobacteria have shown great potential to be used in modern agriculture not only to improve soil fertility but also to enhance utilization of the nutrients, promote crop growth and yield. These organisms stimulate soil microbial activities associated with conversions and mobilization of nutrients in the soil (Alvarez et al., 2021; Renuka et al., 2018). Microalgae are widespread organisms that consist of prokaryotic blue algae, eukaryotic green algae, and gram-negative prokaryotic cyanobacteria. Wastewater provides perfect source of organo-mineral fertilizers of microalgae origin (de Paula Pereira et al., 2021). Biotechnological potential of microalgae and cyanobacteria to maintain soil quality and health is well described by Abinandan et al. (2019).

Microalgae and cyanobacteria contribute to increased soil micro-nutrients through different ways. They increase soil enzymatic activities (Barone et al., 2018; Kusvuran, 2021; Tang et al., 2020), nutrient cycling and recovery (Ali et al., 2021; Li et al., 2019; Nagarajan et al., 2020), biodegradation, bioaccumulation, and biosorption of nutrients (Mustafa et al., 2021), and improve C balance (Jacob-lobes et al., 2020). Wuang et al. (2016) reported increased Zn, Mn, Ca, Fe, and selenium (Se) when microalgae were used as a biofertilizer. A study by Dubey and Dubey (2016) provides evidence of the use of Blue Green Algae (*Chlorella pyrenoidosa* and *Nostoc muscorum*) as soil conditioner in improving soil fertility in a sandy soil. It has also been reported that microalgae and cyanobacteria improve crops metabolic activities and development

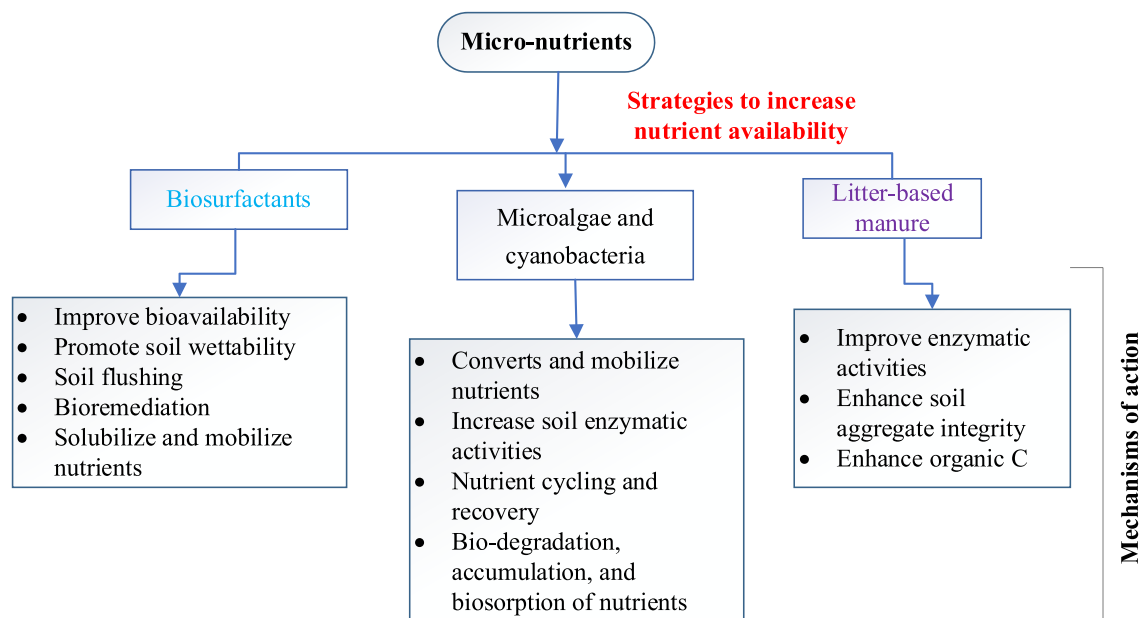


Fig. 2. Approaches to improve soil micro-nutrients and their mechanisms.

(Grzesik and Romanowska-duda, 2015) which translates to higher crop yields. Microalgae increased tomato growth by 49.5% (Munaro et al., 2024) while cyanobacteria increased maize yield by 20.46% to 21.11% (Zambrano et al., 2023).

The organisms can improve crop growth by producing growth hormones, polysaccharides, enzymes, vitamins and antimicrobial compounds, detoxifies harmful substances and controls crop pathogens (Abinandan et al., 2019) leading to increased crop yields. Trejo et al. (2012) reported increased sorghum yield, microbial carbon (C), organic matter and organic C in eroded desert soil treated with a combination of growth promoting bacterium (*Azospirillum brasilense*) and alginate beads with microalgae (*Chlorella sorokiniana*). Rice-associated probiotic bacteria (strains; *Pseudochrobacterum* sp. (BRRh-1), *Burkholderia* sp. (BRRh-2), *Burkholderia* sp. (BRRh-3), *Burkholderia* sp. (BRRh-4), and *Pseudomonas aeruginosa* (BRRh-5 and BRRh-6)) increased rice growth and yield in nutrient-limiting soils (Han et al., 2017). Renuka et al. (2017) found that combining microalgae (*Spirogyra*, *Phormidium*, *Fischerella*, *Westiopsis* and *Anabaena*) with full dose PK, and 75% N caused 35–51% and 37–48% increase in soil organic carbon (SOC) and wheat grain yield, respectively coupled with significantly higher Zn, Fe, Cu and Mn by 20.8, 61.3, 36.9, and 25.9%, respectively. Increased tomato and broccoli yields have also been reported when they were grown under microalgae and/or their extracts (Barone et al., 2018; Kusvuran, 2021).

3.1.3. Compost, farmyard and green manure application

Compost, farmyard (FYM) and green manure are cheaper options of soil fertilization common in most SSA countries and often been used as source of NPK (Batabyal et al., 2016; Hadi et al., 2021; Mugwe et al., 2009), with little to no attention being used as a major source of micronutrients. However, these organic-based fertilizers are promising micronutrient management strategies. The efficiency of these inputs to improve soil micronutrients depend largely on the quality and the correct rate of application (Baldi et al., 2021; Batabyal et al., 2016). The importance of organic-based fertilization is evidenced in the long-term study conducted over a period of 14 years where application of the inputs at 5–10 t annually significantly improved cadmium (Cd), Zn and copper (Cu) by 5.9, 13.7, and 15.7% to permissible levels without posing environmental risks (Baldi et al., 2021). Organic inputs contain beneficial organisms that can solubilize and enhance bioavailability of micronutrients (Ongeng et al., 2011). A review by Corato (2020) has established beneficial effects of combining compost with a wide range of microbes like bacteria, yeast, protists, actinomycetes, fungi and oomycetes on yield and soil micro-nutrients. Bedada et al. (2016) reported that application of half rates of compost (13.5 t ha⁻¹ fresh weight or 1.4 t ha⁻¹ dry weight organic matter) and mineral fertilizer (50 kg di-ammonium phosphate ha⁻¹ + 25 kg urea ha⁻¹) increased boron (B), Mn, Cu, and Zn by 20.9, 6.2, 6.9, 8.9% with a resultant mean maize yield benefit of 0.7 t ha⁻¹.

Green manure (GM) increased microbial biomass C by 28%, and improved soil enzymatic activities approximately by 14 to 39% (Ma et al., 2021). The type of green manure affects soil nutrients differently. Green manure improves soil organic carbon (SOC), especially when combined with NPK fertilizer (Kamran et al., 2021; Mucheru-Muna et al., 2007) which in turn has positive significant effect on micronutrients (Romaniuk et al., 2018; Sharma et al., 2013). Effect of green manure on aggregate stability has been widely investigated (Garcia-Franco et al., 2015; Guo et al., 2019; Kamran et al., 2021). The net effect of improved aggregate stability on micronutrients are indirect through improved SOC sequestration within aggregates (Kamran et al., 2021) and directly through protection against leaching and runoffs. Green manure promotes chelation of micronutrients and improve their bioavailability to both plants and soil microorganisms. Chelating agents (diethylenetriaminepentaacetic acid) are increasingly gaining importance in replenishing and measuring chelated micronutrients from various non-recalcitrant pools (Kopittke et al., 2017).

3.1.4. Mediating factors that indirectly enhance micronutrients in the soil

Micronutrients concentration in the soil can also be improved by mediating factors, acting independently, or interacting with sources of the nutrients. For instance, it has been reported that crop intensification sequence, measured by intensification sequence index (ISI), improved micronutrients like Zn, Fe, and Cu (Romaniuk et al., 2018). Elsewhere, Sharma and Dhaliwal (2021) found increased levels of crystalline-bound Zn, Fe and Mn under zero tillage with residue retention. Wang et al. (2017) reported increased extractable Fe, Mn and Cu concentrations by 262, 150, and 55% under N addition.

Agronomic approaches such as mineral fertilizer application and water management regulate soil micronutrient availability for enhanced plant uptake (Rengel et al., 1999). Masunaga and Marques (2018) while working with paddy system found that the establishment of flooded water conditions increased Fe and Mn availability by over 200 mg kg⁻¹ while Zn and availability increased by between 9.10 and 49.23 mg kg⁻¹. Copper availability in the soil ranged between 2.34 and 10.50 mg kg⁻¹ when farm yard manure was combined with water management in the paddy field (Masunaga and Marques, 2018). Masunaga and Marques (2018) also reported that farmyard manure application significantly increased grain Fe concentration under any water condition compared to control and chemical fertilizer treatments. Masunaga and Marques (2018) also found that concentration of Zn and Cu in grain produced the best results under field capacity water conditions while Mn concentration did not correspond to soil Mn availability. These findings demonstrate the need for innovative practices and/or strategies that can supplement or complement the available direct sources of micronutrients. Furthermore, practices that encourage organic matter build-up are sustainable sources of Zn, Cu, Fe, Mn, B and Mo (Dhaliwal et al., 2019).

3.2. Strategic research in the domain of secondary nutrients

Weathering of primary and secondary minerals is the main source of secondary nutrients in soils (Hillel, 2004; Wilson, 2004). However, this nature-driven phenomenon cannot sustain the current and projected crop production levels. Mineral fertilizers containing Mg, S and Ca is the conventional approach to replenishing these nutrients in the contemporary practices (Ding et al., 2021; Skórzyńska-Polit et al., 1998; Trumbull and Slack, 2018). Dolomitic lime (CaMg(CO₃)₂) stands as one of the most important sources of Ca and Mg (Cai et al., 2021). The other sources of Mg included magnesium oxide (MgO) and magnesium chloride (Yousaf et al., 2021). On the other hand, S supplements include K and Mg sulfate, gypsum (calcium sulfate; CaSO₄) and elemental sulfur (Bhaduri et al., 2014).

Previous studies have demonstrated the effect of varying approaches to improving soil secondary nutrients for enhanced agricultural productivity. For instance, Shambhavi et al. (2018) observed that a combination of NPK and farmyard manure increased S, Mg and Ca only when lime was added. Shambhavi et al. (2018) point out the importance of supplementing NPK fertilizers with Mg and Ca to sustain crop production while maintaining soil fertility. Polysulphate® is being proposed as a source of both macro- and secondary nutrients. The product is available in its natural state and contains 19.2% S, 3.6% Mg, and 12.2% Ca. The impact of application of polysulphate at the rate of 125% of the soil test was manifested on superior secondary nutrients concentrations and increased tomato yield by 39.3% (Pandian, 2019).

Sulfur polymer composites have been taunted as a more sustainable and an emergent option to increasing soil fertility and release of both macro- and secondary nutrients in a controlled pattern which reduces cases of nutrients wastage (Mann et al., 2019). The most common polymers used with mineral fertilizers include chitosan, starch, and alginate. For instance, Chiaregato et al. (2022) demonstrated better Mg, Ca and S release when NPK and potassium nitrate were combined with cross-linked polymers. Moreover, coating urea and NPK fertilizers with S has been proposed, tested, and recommended for sustained provision of

both macro and secondary nutrients (Chagas et al., 2020; Liu et al., 2008). A study has also demonstrated the potential of polyhalite, hydrated sulfates of K, Ca and Mg, a source of Mg and Ca in addition to other soil nutrients (Yermiyahu et al., 2017).

There exist conventional approaches to managing soil micro- and secondary nutrients and soil acidity. These include but not limited to; strategic integrated soil fertility management (ISFM), biochar, and foliar application. For instance, integrating NPK fertilizers with organic inputs improve the nutrients under varying cropping systems and soil types (Kang et al., 2022). Whereas organic manure increases utilization efficiency of NPK fertilizer, the fertilizer enhances decomposition/mineralization of the litter to release the nutrients into the soil solution. Previous studies have reported higher micro and secondary nutrients from diverse types of manure (Agbede, 2021; Somers et al., 2020). Biochar application show great potential to improving secondary and micronutrients both in acidic (Yan et al., 2021) and alkaline agricultural soils. Foliar fertilization is the quickest way of providing plants with readily available nutrients, especially secondary and micro-nutrients. Khodaparast et al. (2021) found that foliar application of zinc sulfate and zinc nanoparticles at 10 mg/L significantly improved yield performance of coffee.

3.3. Soil acidity and amelioration strategies

Soil acidity is possibly the single most important cause of hidden hunger at plot and farm levels in sub- and tropic soils where leaching of base cations and anthropogenic-induced acidity are rampant (Kihara et al., 2017). This is because the effects of low soil pH are often masked by deficiency symptoms of other nutrients (Nduwumuremyi et al., 2013). Adverse effects of high soil acidity and aluminum (Al) toxicity on enzyme activities and soil macro- (e.g. K and P), secondary- (Mg and Ca) and micronutrients (Cu, Zn and Mo) have been documented (Nduwumuremyi et al., 2013; Zhou et al., 2019). Factors that contribute to increased soil acidity include; application of acidifying inorganic fertilizers, continuous cropping, leaching of nutrients and inherent nature of acidic parent rocks among others.

Many strategies, including use of organic inputs, optimum use of inorganic fertilizer, application of liming materials, and integration of these measures. Lime application remains the most widely known conventional strategy in the management of acidity in varying soil types and crops (Harun et al., 2015; Serafim et al., 2013; Toksöz and Yilmaz, 2021; Yin et al., 2021). For instance, lime application increased yield of major crops such as; soybeans, maize, barley, tef, faba beans, wheat potato and maize by 28–182% across Eastern Africa. Despite the importance of lime being a key acidity management practice, its adoption is still low even in regions with strongly high soil acidity. Factors leading to the low adoption of lime application in such instances is less comprehensive and not strongly expressed in the available literature.

Liming is a widespread agricultural practice in acidic soils used to primarily improve crop productivity. Lime application may change array of soil physical, chemical and biological properties (Bölscher et al., 2021). For instance, modern empirical studies have reported multifaceted functions of lime; improving soil structure (Bölscher et al., 2021; Das et al., 2021; Khodaparast et al., 2021), enhancing microbial diversity (Li et al., 2021), promoting biological N fixation (Alves et al., 2021), and stabilization of clay soils (Baldovino et al., 2021; Kumar, 2021; Toksöz and Yilmaz, 2021). Lime application also protects against phosphorus (P) leaching from clay soils where its transport predominantly occurs attached on soil colloids through preferential flow paths (Svanbäck et al., 2014; Taylor et al., 2014). Recently, a study conducted in Western Kenya revealed that lime increased maize yield by 2 t ha⁻¹ for soil with pH range of 4.0 – 5.7, which was even made better when combined with N and P fertilizer and that investment in liming paid off at least after 2 years (Hijbeek et al., 2021). Nevertheless, there is concern that the knowledge on liming effect on other important properties, like soil microbiome, is still limited (Yin et al., 2021).

Type, timing and placement of lime are important management and handling information that can enhance lime use efficiency. Yin et al. (2021) found a reducing soil acidity with the increasing lime application rates while its application at the rate of 9% of the soil dry weight had superior improvement of Indian black cotton relative to 3%, 6%, and 12% rates (Singh et al., 2021). Lack of assessment of lime use efficiency is the biggest limitation in lime studies which needs consideration in the subsequent experiments.

There are several liming materials that vary on the influence they exert on soil properties. The conventional materials include; quicklime (CaO), hydrated quicklime (Ca(OH)₂), calcium carbonate (CaCO₃), mixture of Ca(OH)₂ and CaCO₃ (Peters et al., 1996). However, the need to reduce pressure on naturally-occurring and non-renewable materials, more sustainable liming materials have been discovered. For instance, Life Cycle Assessment have shown that eggshell lime is a sustainable and more efficient soil stabilization liming material than the commercially-available limes (Saldanha et al., 2021). Emergent liming materials in Kenya include Dolo, Calcipril, and Ag lime, among others. Nevertheless, lime material markets are greatly limited or non-existent in several regions, even in areas that have prevalent soil acidity problems (Oumer et al., 2023).

3.4. Research in the domain of 4Rs stewardship

Developed by the International Plant Nutrition Institute (IPNI) after many years of research, the 4Rs stewardship is the realm of the balanced plant nutrition which is key for sustainable crop production and soil fertility maintenance (Fig. 3). The approach provides a science-based framework that champions the best utilization of fertilizers. The 4Rs stewardship ensures provision of all the 17 essential nutrients, i.e., macro, micro and secondary nutrients in the; i) right source, ii) right rate, iii) right time, and iv) right placement, to sustain crop production without depleting soil nutrient reserves (Oumer et al., 2023). This novelty takes into account the; society, environment and economics dynamics in agricultural production (Vollmer-Sanders et al., 2016). An example of the functionality of the 4Rs is demonstrated by Syers et al. (2010) providing instances of improved grain yield, nutrient use efficiency and profitability.

With the increasing need for fertilizer best management practices, the 4Rs provides a strong foundation that supports improved nutrient use efficiency, and environmental integrity while enhancing farmer's profitability (Johnston and Bruulsema, 2014). Using fruit crops, Bryla (2020) gives detailed view of the four factors; right sources; right time, right source and right place that substantially enhanced the yield and growth parameters of primocanes, floricanes, blueberry, and pineapple. Mattson and Iersel (2011), Mikkelsen (2011), and Scandinavica et al. (2017) amplified the importance of the 'right time' and 'right place' of the 4Rs Stewardship on horticultural crops. On the other hand, Bruulsema et al. (2019) showcased the application of the 4R Stewardship in P management across different latitudes with different temperature regimes and soil types.

The importance of the 4Rs is underlined by the increasing number of contemporary studies that assess the four factors of the Stewardship. However, the majority of the studies rarely consider the factors holistically but evaluates only one or two at a time. For example, Spinelli et al. (2013) did an environmental analysis of sunflower produced under different fertilizer forms. On their part, Song et al. (2022) confirmed the biophysical advantage of using the right source and right rate on a paddy soil. Generally, the right fertilizer rate positively affect crop rooting systems, yield, and soil physicochemical properties that not only secures environmental health but also offers the best economical returns to the farmers (Adebayo and Sebetha, 2020; Li et al., 2015; Song and Lin, 2014). Other studies have also outlined the importance and nutrient use efficiency of the right timing of fertilization in several crops like maize, wheat, orchards, peanuts (Hussain et al., 2015; Liu et al., 2018; Momesso et al., 2022; Wu et al., 2019). Him et al. (2019) evaluated the

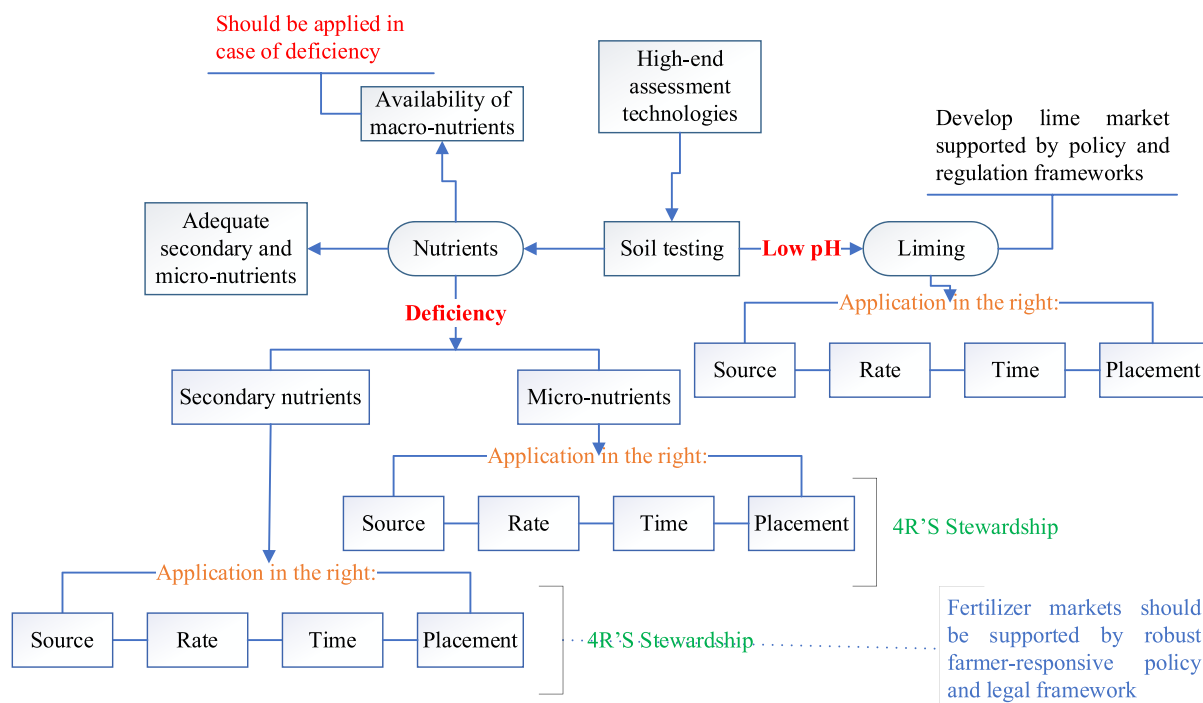


Fig. 3. Policy and legal-based balanced nutrition framework for soil fertility management.

effect of fertilizer N application rate and timing while Gildow et al. (2016) assessed timing and placement as means to reducing P loading into Lake Erie.

From the above highlights, it is apparent that the current literature, though appreciative of the four factors of the 4Rs, the contemporary research has dodged incorporating all the four factors into a single study. With this shortfall, the need for 4R Nutrient Stewardship Certification Program in croplands is pertinent.

4. Challenges in modern and future outlook in soil fertility research in SSA

Next generation soil fertility management studies will be robust and supported by high-end assessment technologies. The use of bio-surfactants, industrial and domestic effluents will not only provide irrigation water but also be crucial sources of micro- and secondary nutrients in SSA. Future fertilization programs will be more effective if they will combine conventional (mineral and organic fertilizers) and/or non-conventional methods like biosurfactants, textiles effluents and microalgae. This should be accompanied by supportive policy and legal frameworks to regulate fertilizer use and market for the produce. The need for soil testing to understand its status coupled with investments in awareness will grow to be key in all fertilization programs. Further, robust extension service providers and stockists capacity building will be critical in taking the next bold step to holistic improvement of soil fertility for the more demanding population.

5. Conclusion and recommendation

Low soil secondary and micro-nutrients and acidity problems are indicated by the response of yields of various crops to the application of secondary, micro-nutrients and liming. Combination of lime and fertilizers has better effect on soil and yield than sole applications. Lime adoption by smallholder farmers is restricted by lime markets which are scarce in areas with profound acidic soils. Developing lime supply chain in areas with no assisting supply chains is expensive. Moreover, fertilizer and lime markets development are affected by lack of robust policy,

legal framework and political goodwill. Addressing these challenges require formulation of robust policy and legal frameworks in fertilizer and lime markets dynamics. More secondary and micro-nutrient-specific empirical studies should be promoted. Furthermore, mineral fertilizer blends should include micro and secondary nutrients. Though extent of micronutrients deficiencies per land basis has been estimated, there is need for objective assessment of the extent of deficiencies in quantity basis.

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CRedit authorship contribution statement

E.O. Otieno: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M.W. Mucheru-Muna:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **M.N. Kifuko-Koech:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **C.N. Kamau:** Visualization, Validation, Project administration, Investigation, Conceptualization. **K.W. Ndung'u-Magiroi:** Writing – original draft, Supervision, Resources, Project administration, Funding acquisition. **H. Mogaka:** Writing – review & editing, Visualization, Validation, Supervision, Methodology. **J.N. Mugwe:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

References

- Abinandan, S., Subashchandrabose, S.R., Megharaj, M., 2019. Critical Reviews in Biotechnology Soil microalgae and cyanobacteria : the biotechnological potential in the maintenance of soil fertility and health. *Crit. Rev. Biotechnol.* 0, 1–18. <https://doi.org/10.1080/07388551.2019.1654972>.
- Adebayo, A.R., Sebetha, E.T., 2020. Data on influence of different nitrogen fertilizer rates and plant density on grain yield and yield components of Water Efficient Maize (WEMA) variety. *Data Brief* 30, 105582. <https://doi.org/10.1016/j.dib.2020.105582>.
- Agbede, T.M., 2021. Effect of tillage, biochar, poultry manure and NPK 15-15-15 fertilizer, and their mixture on soil properties, growth and carrot (*Daucus carota* L.) yield under tropical conditions. *Heliyon* 7 (6), e07391. <https://doi.org/10.1016/j.heliyon.2021.e07391>.
- Agegehu, G., Amede, T., Erkossa, T., Yirga, C., Tyler, R., Nosworthy, M.G., Beyene, S., Gudeta, W., 2021. Extent and management of acid soils for sustainable crop production system in the tropical agroecosystems : a review. *Acta Agric. Scand. Sect. B Soil Plant Sci.* 71, 852–869. <https://doi.org/10.1080/0964710.2021.1954239>.
- Ahmad, Z., Imran, M., Qadeer, S., 2018. Biosurfactants for sustainable soil management. *Advances in Agronomy*, 1st ed. Elsevier Inc. <https://doi.org/10.1016/bi.agron.2018.02.002>.
- Alejandro, S., Höller, S., Meier, B., Peiter, E., 2020. Manganese in plants: from acquisition to subcellular allocation. *Front. Plant Sci.* 11, 1–23. <https://doi.org/10.3389/fpls.2020.00300>.
- Ali, S., Nejad, G., & Etesami, H. (2020). *The importance of boron in plant nutrition* (D. Rupesh, D. K. Tripathi, & G. Guerriero (Eds.); 1st ed., Vol. 1). John Wiley & Sons Ltd.
- Ali, S., Paul Peter, A., Wayne Chew, K., Siti Halimatul Munawaroh, H., Loke Show, P., 2021. Resource recovery from industrial effluents through the cultivation of microalgae: a review. *Bioresour. Technol.* 23, 125461 <https://doi.org/10.1016/j.biortech.2021.125461>.
- Alloway, B.J., 2008. *Micronutrient Deficiencies in Global Crop Production*.
- Alves, L.A., Ambrosini, V.G., Denardin, L.G., de, O., Flores, J.P.M., Martins, A.P., Filippi, D., Bremm, C., Carvalho, P.C., de, F., Farias, G.D., Ciampitti, I.A., Tiecher, T., 2021. Biological N₂ fixation by soybeans grown with or without liming on acid soils in a no-till integrated crop-livestock system. *Soil Tillage Res.* 209, 104923 <https://doi.org/10.1016/j.still.2020.104923>.
- Baccile, N., 2023. Are microbial biosurfactants actually only surfactants? *Curr. Opin. Colloid Interface Sci.* 68, 101747 <https://doi.org/10.1016/j.cocis.2023.101747>.
- Baldi, E., Cavani, L., Mazzon, M., Marzadori, C., Quartieri, M., Toselli, M., 2021. Fourteen years of compost application in a commercial nectarine orchard: effect on microelements and potential harmful elements in soil and plants. *Sci. Total Environ.* 752, 141894 <https://doi.org/10.1016/j.scitotenv.2020.141894>.
- Baldovino, J.J.A., Izzo, R.L.S., Rose, J.L., Domingos, M.D.I., 2021. Strength, durability, and microstructure of geopolymers based on recycled-glass powder waste and dolomitic lime for soil stabilization. *Constr. Build. Mater.* 271, 121874 <https://doi.org/10.1016/j.conbuildmat.2020.121874>.
- Barone, V., Puglisi, I., Fragalà, F., Sidella, S., 2018. Effect of living cells of microalgae or their extracts on soil enzyme activities. *Arch. Agron. Soil Sci.* 0, 12–23. <https://doi.org/10.1080/03650340.2018.1521513>.
- Batabyal, K., Mandal, B., Sarkar, D., Murrnu, S., Tamang, A., Das, I., Chand, G., Sarathi, P., 2016. Comprehensive assessment of nutrient management technologies for cauliflower production under subtropical conditions. *Eur. J. Agron.* 79, 1–13. <https://doi.org/10.1016/j.eja.2016.04.009>.
- Bedada, W., Lemenih, M., Karlun, E., 2016. Soil nutrient build-up, input interaction effects and plot level N and P balances under long-term addition of compost and NP fertilizer. *Agric. Ecosyst. Environ.* 218, 220–231. <https://doi.org/10.1016/j.agee.2015.11.024>.
- Bertoldo, G., Lucia, M.C.D., Baghdadi, A., Mangione, F., Cagnin, M., Chiodi, C., Concheri, G., Stevanato, P., Nardi, S., 2023. Molecular and ionic responses of *Solanum lycopersicum* L. (cv. Micro-Tom) plants treated with a novel calcium-based plant biostimulant. *Plant Gene* 34, 100408. <https://doi.org/10.1016/j.plgene.2023.100408>.
- Bhaduri, D., Rakshit, R., Chakraborty, K., 2014. Primary and secondary nutrients—a boon to defense system against plant diseases. *Int. J. Bio-Resource Stress Manage.* 5 (3), 461. <https://doi.org/10.5958/0976-4038.2014.00597.1>.
- Bölscher, T., Koestel, J., Etana, A., Ulén, B., Berglund, K., Larsbo, M., 2021. Changes in pore networks and readily dispersible soil following structure liming of clay soils. *Geoderma* 390 (January), 114948. <https://doi.org/10.1016/j.geoderma.2021.114948>.
- Brullesma, T.W., Peterson, H.M., Prochnow, L.I., 2019. The science of 4R nutrient stewardship for phosphorus management across latitudes. *J. Environ. Qual.* 48 (5), 1295–1299. <https://doi.org/10.2134/jeq2019.02.0065>.
- Bryla, D.R., 2020. 4R nutrient stewardship in fruit crops. *Fruit Crops*. <https://doi.org/10.1016/B978-0-12-818732-6.00036-8>.
- Cai, W.K., Liu, J.H., Zhou, C.H., Keeling, J., Glasmacher, U.A., 2021. Structure, genesis and resources efficiency of dolomite: new insights and remaining enigmas. *Chem. Geol.* 573, 120191 <https://doi.org/10.1016/j.chemgeo.2021.120191>.
- Chagas, J.O., Gomes, J.M., Cunha, I.C., de, M., de Melo, N.F.S., Fraceto, L.F., da Silva, G. A., Lobo, F.A., 2020. Polymeric microparticles for modified release of NPK in agricultural applications. *Arabian J. Chem.* 13 (1), 2084–2095. <https://doi.org/10.1016/j.arabjch.2018.03.007>.
- Chianu, J.N., Chianu, J.N., Mairura, F., 2012. Mineral fertilizers in the farming systems of sub-Saharan Africa. A review. *Agron. Sustain. Dev.* 32 (2), 545–566. <https://doi.org/10.1007/s13593-011-0050-0>.
- Chiaregato, C.G., França, D., Messa, L.L., dos Santos Pereira, T., Faez, R., 2022. A review of advances over 20 years on polysaccharide-based polymers applied as enhanced efficiency fertilizers. *Carbohydr. Polym.* 279, 119014 <https://doi.org/10.1016/j.carbpol.2021.119014>.
- Cole, J.C., Smith, M.W., Penn, C.J., Cheary, B.S., Conaghan, K.J., 2016. Nitrogen, phosphorus, calcium, and magnesium applied individually or as a slow release or controlled release fertilizer increase growth and yield and affect macronutrient and micronutrient concentration and content of field-grown tomato plants. *Sci. Hortic.* 211, 420–430. <https://doi.org/10.1016/j.scienta.2016.09.028>.
- Corato, U.De, 2020. Agricultural waste recycling in horticultural intensive farming systems by on-farm composting and compost-based tea application improves soil quality and plant health : a review under the perspective of a circular economy. *Sci. Total Environ.* 738, 139840 <https://doi.org/10.1016/j.scitotenv.2020.139840>.
- Das, A.J., Ambust, S., Singh, T., Kumar, R., 2021a. Biosurfactant assisted design treatments for remediation of petroleum contaminated soil and metabolomics based interactive study with *Brassica nigra* L. *Environ. Challenges* 4, 100080. <https://doi.org/10.1016/j.envc.2021.100080>.
- Das, G., Razakamanantsoa, A., Herrier, G., Saussaye, L., Lesueur, D., Deneele, D., 2021b. Evaluation of the long-term effect of lime treatment on a silty soil embankment after seven years of atmospheric exposure: mechanical, physicochemical, and microstructural studies. *Eng. Geol.* 281 (10), 105986 <https://doi.org/10.1016/j.enggeo.2020.105986>.
- de Paula Pereira, A.S.A., de Siqueira Castro, J., Ribeiro, V.J., Calijuri, M.L., 2021. Organomineral fertilizers pastilles from microalgae grown in wastewater: ammonia volatilization and plant growth. *Sci. Total Environ.* 779, 146205 <https://doi.org/10.1016/j.scitotenv.2021.146205>.
- Dhaliwal, S.S., Naresh, R.K., Mandal, A., Singh, R., Dhaliwal, M.K., 2019. Dynamics and transformations of micronutrients in agricultural soils as influenced by organic matter build-up: a review. *Environ. Sustain. Indic.* 1–2, 100007 <https://doi.org/10.1016/j.indic.2019.100007>.
- Ding, T., Tao, C., Dias, A.A., Liang, J., Chen, J., Wu, B., Ma, D., Zhang, R., Wang, J., Liao, S., Wang, Y., Yang, W., Liu, J., Li, W., Zhang, G., Huang, H., 2021. Sulfur isotopic compositions of sulfides along the Southwest Indian Ridge: implications for mineralization in ultramafic rocks. *Mineralium Deposita* 56, 991–1006. <https://doi.org/10.1007/s00126-020-01025-0>.
- Doncato, K.B., Costa, C.S.B., 2021. Micronutrient supplementation needs for halophytes in saline aquaponics with BFT system water. *Aquaculture* 531 (July 2020), 735815. <https://doi.org/10.1016/j.aquaculture.2020.735815>.
- Dubey, A., Dubey, D.K., 2016. Evaluation of cost effective organic fertilizers. *Int. J. Agric. Crop Sci.* 15, 283–287.
- FAO. (2019). *World Food and Agriculture Statistical Pocketbook*.
- García-Franco, N., Albaladejo, J., Almagro, M., Martínez-Mena, M., 2015. Beneficial effects of reduced tillage and green manure on soil aggregation and stabilization of organic carbon in a Mediterranean agroecosystem. *Soil Tillage Res.* 153, 66–75. <https://doi.org/10.1016/j.still.2015.05.010>.
- Geng, G., Cakmak, I., Ren, T., Lu, Z., Lu, J., 2021. Effect of magnesium fertilization on seed yield, seed quality, carbon assimilation and nutrient uptake of rapeseed plants. *Field Crops Res.* 264, 108082 <https://doi.org/10.1016/j.fcr.2021.108082>.
- Gildow, M., Aloysius, N., Gebremariam, S., Martin, J., 2016. Fertilizer placement and application timing as strategies to reduce phosphorus loading to Lake Erie. *J. Great Lakes Res.* 1–8. <https://doi.org/10.1016/j.jglr.2016.07.002>.
- Greaney, A.T., Rudnick, R.L., Gaschnig, R.M., Whalen, J.B., Luais, B., Clemens, J.D., 2018. Geochemistry of molybdenum in the continental crust. *Geochim. Cosmochim. Acta* 238, 36–54. <https://doi.org/10.1016/j.gca.2018.06.039>.
- Griffith, E.M., Schmitt, A.D., Andrews, M.G., Fantle, M.S., 2020. Elucidating modern geochemical cycles at local, regional, and global scales using calcium isotopes. *Chem. Geol.* 534, 119445 <https://doi.org/10.1016/j.chemgeo.2019.119445>.
- Grzebisz, W., Zielewicz, W., Przygocka-Cyna, K., 2023. Deficiencies of secondary nutrients in crop plants—A real challenge to improve nitrogen management. *Agronomy* 13, 1–30. <https://doi.org/10.3390/agronomy13010066>.
- Grzesik, M., Romanowska-duda, Z., 2015. Ability of cyanobacteria and green algae to improve metabolic activity and development of willow plants. *Polish J. Environ. Stud.* 24 (3), 1003–1012. <https://doi.org/10.15244/pjoes/34667>.
- Guo, Z., Zhang, J., Fan, J., Yang, X., Yi, Y., Han, X., Wang, D., Zhu, P., Peng, X., 2019. Does animal manure application improve soil aggregation? Insights from nine long-term fertilization experiments. *Sci. Total Environ.* 660, 1029–1037. <https://doi.org/10.1016/j.scitotenv.2019.01.051>.
- Gurmessa, B., 2021. Soil acidity challenges and the significance of liming and organic amendments in tropical agricultural lands with reference to Ethiopia. *Environ. Dev. Sustain.* 23, 77–99. <https://doi.org/10.1007/s10668-020-00615-2>.

- Hadi, M., Ghalavand, A., Boojar, M.M., 2021. Application of manure and biofertilizer to improve soil properties and increase grain yield, essential oil and ω 3 of purslane (*Portulaca oleracea* L.) under drought stress. *Soil Tillage Res.* 205, 104633 <https://doi.org/10.1016/j.still.2020.104633>.
- Han, M.A.K., Aque, E.H., Aul, N.C.P., Haleque, A.K., Arni, S.M.S.A.L., Ahman, M.R., Slam, T.I., 2017. Enhancement of growth and grain yield of rice in nutrient deficient soils by rice probiotic bacteria. *Rice Sci.* 24, 264–273. <https://doi.org/10.1016/j.rsci.2017.02.002>.
- Harun, I.G., Benson, E.M., Benjamin, O.D., 2015. Effect of lime and goat manure on soil acidity and maize (*Zea mays*) growth parameters at Kavutiri, Embu County- Central Kenya. *J. Soil Sci. Environ. Manage.* 6 (10), 275–283. <https://doi.org/10.5897/jssm15.0509>.
- Hijbeek, R., van Loon, M.P., Ouaret, W., Boekelo, B., van Ittersum, M.K., 2021. Liming agricultural soils in Western Kenya: can long-term economic and environmental benefits pay off short term investments? *Agric. Syst.* 190, 103095 <https://doi.org/10.1016/j.agsy.2021.103095>.
- Hillel, D. (2004). *Encyclopedia of soils in the environment* (D. Hillel, J. Hatfield, K. Scow, D. Powlson, M. Singer, C. Rosenzweig, & D. Sparks (eds.); First Edit).
- Him, T., Rudnick, D.R., Burr, C.A., Stockton, M.C., Werle, R., 2019. Approaches to evaluating grower irrigation and fertilizer nitrogen amount and timing. *Agric. Water Manage.* 693–706. <https://doi.org/10.1016/j.agwat.2018.11.010>.
- Hussain, S., Anwar-ul-haq, M., Hussain, S., Akram, Z., 2015. Best suited timing schedule of inorganic NPK fertilizers and its effect on qualitative and quantitative attributes of spring sown sugarcane (*Saccharum officinarum* L.). *J. Saudi Soc. Agric. Sci.* 33, 0–5. <https://doi.org/10.1016/j.jssas.2015.02.004>.
- Jacob-lobes, E., Santos, B., Severo, I.A., Depr, M.C., Maroneze, M.M., Zepka, L.Q., 2020. Dual production of bioenergy in heterotrophic cultures of cyanobacteria : process performance, carbon balance, biofuel quality and sustainability metrics. *Biomass Bioenergy J.* 142, 105756 <https://doi.org/10.1016/j.biombioe.2020.105756>.
- Jassim, R.Z., Al-Badri, A.S., 2019. Mineral resources and occurrences of sodium chloride in Iraq: an overview. *Iraqi Bull. Geol. Min.* 8, 263–287.
- Johnston, A.M., Bruulsema, T.W., 2014. 4R nutrient stewardship for improved nutrient use efficiency. *Procedia Eng.* 83, 365–370. <https://doi.org/10.1016/j.proeng.2014.09.029>.
- Kamarudin, K.N., Tomita, M., Kondo, K., Abe, S.S., 2020. Spatial variation and distribution of soil micronutrients relative to macronutrients in Mt. Wakakusa Grassland (central-western Japan). *Landscape Ecol. Eng.* 16, 335–343. <https://doi.org/10.1007/s11355-020-00424-9>.
- Kamran, R., Huang, L., Nie, J., Geng, M., Lu, Y., Liao, Y., Zhou, F., Xu, Y., 2021. Effect of reduced mineral fertilization (NPK) combined with green manure on aggregate stability and soil organic carbon fractions in a fluvo-aquic paddy soil. *Soil Tillage Res.* 211, 105005 <https://doi.org/10.1016/j.still.2021.105005>.
- Kang, J.T., Ionov, D.A., Zhu, H.L., Liu, F., Zhang, Z.F., Liu, Z., Huang, F., 2019. Calcium isotope sources and fractionation during melt-rock interaction in the lithospheric mantle: evidence from pyroxenites, wehrlites, and eclogites. *Chem. Geol.* 524, 272–282. <https://doi.org/10.1016/j.chemgeo.2019.06.010>.
- Kang, Y.-G., Lee, J.-H., Chun, J.-H., Yun, Y.-U., Atef Hatamleh, A., Al-Dosary, M.A., Al-Wasel, Y.A., Lee, K.-S., Oh, T.-K., 2022. Influence of individual and co-application of organic and inorganic fertilizer on NH₃ volatilization and soil quality. *J. King Saud Univ. Sci.* 34, 102068 <https://doi.org/10.1016/j.jksus.2022.102068>.
- Khodaparast, M., Rajabi, A.M., Mohammadi, M., 2021. Mechanical properties of silty clay soil treated with a mixture of lime and zinc oxide nanoparticles. *Constr. Build. Mater.* 281, 122548 <https://doi.org/10.1016/j.conbuildmat.2021.122548>.
- Kihara, J., Bolo, P., Kinyua, M., Rurinda, J., Piikki, K., 2020. Micronutrient deficiencies in African soils and the human nutritional nexus: opportunities with staple crops. *Environ. Geochem. Health* 42, 3015–3033. <https://doi.org/10.1007/s10653-019-00499-w>.
- Kihara, J., Sileshi, G.W., Nziguheba, G., Kinyua, M., Zingore, S., Sommer, R., 2017. Application of secondary nutrients and micronutrients increases crop yields in sub-Saharan Africa. *Agron. Sustain. Dev.* 37, 25. <https://doi.org/10.1007/s13593-017-0431-0>.
- Kistler, R.B., Helvaci, C., 1994. Boron and Borates. *Ind. Miner. Rocks* 171–186. <http://ki.si.edu.edu.tr/cahit.helvaci/Boron.pdf>.
- Kleinen, J., 2023. Will Biosurfactants replace conventional surfactants? *Curr. Opin. Colloid Interface Sci.* <https://doi.org/10.1016/j.cocis.2023.101764>.
- Kopitke, P.M., Dalal, R.C., Menzies, N.W., 2017. Changes in exchangeable cations and micronutrients in soils and grains of long-term, low input cropping systems of subtropical Australia. *Geoderma* 285 (3), 293–300. <https://doi.org/10.1016/j.geoderma.2016.10.011>.
- Kopriva, S., Malagoli, M., Takahashi, H., 2019. Sulfur nutrition: impacts on plant development, metabolism, and stress responses. *J. Exp. Bot.* 70, 4069–4073. <https://doi.org/10.1093/jxb/erz319>.
- Kumar, M., 2021. Clay soil stabilization by utilizing secondary lime and rubber tire powder. *Mater. Today Proc.* 37, 3471–3474. <https://doi.org/10.1016/j.matpr.2020.09.383>.
- Kumar, M., Babel, A.L., 2011. Available micronutrient status and their relationship with soil properties of Jhunjhunu Tehsil, District Jhunjhunu, Rajasthan, India. *J. Agric. Sci.* 3, 97–106. <https://doi.org/10.5539/jas.v3n2p97>.
- Kusvuran, S., 2021. Microalgae (*Chlorella vulgaris* Beijerinck) alleviates drought stress of broccoli plants by improving nutrient uptake, secondary metabolites, and antioxidative defense system. *Hortic. Plant J.* 7, 221–231. <https://doi.org/10.1016/j.hpj.2021.03.007>.
- Li, H., Cong, R., Ren, T., Li, X., Ma, C., Zheng, L., Zhang, Z., Lu, J., 2015. Yield response to N fertilizer and optimum N rate of winter oilseed rape under different soil indigenous N supplies. *Field Crops Res.* 181, 52–59. <https://doi.org/10.1016/j.fcr.2015.06.012>.
- Li, K., Liu, Q., Fang, F., Luo, R., Lu, Q., Zhou, W., Huo, S., Cheng, P., Liu, J., Addy, M., Chen, P., Chen, D., Ruan, R., 2019. Bioresource technology microalgae-based wastewater treatment for nutrients recovery : a review. *Bioresour. Technol.* 291, 121934 <https://doi.org/10.1016/j.biortech.2019.121934>.
- Li, S., Ji, X., Chao, C., Liu, Z., Zhu, J., Peng, H., 2021. Effects of increasing lime application rates on microbial diversity and community structure in paddy soils. *Appl. Soil Ecol.* 161 (17), 103837 <https://doi.org/10.1016/j.apsoil.2020.103837>.
- Liu, Y.H., Wang, T.J., Qin, L., Jin, Y., 2008. Urea particle coating for controlled release by using DCPD modified sulfur. *Powder Technol.* 183, 88–93. <https://doi.org/10.1016/j.powtec.2007.11.022>.
- Liu, Z., Gao, F., Liu, Y., Yang, J., Zhen, X., Li, X., Li, Y., Zhao, J., Li, J., Qian, B., Yang, D., Li, X., 2018. Timing and splitting of nitrogen fertilizer supply to increase crop yield and efficiency of nitrogen utilization in a wheat – peanut relay intercropping system in China. *Crop J.* 7, 101–112. <https://doi.org/10.1016/j.cj.2018.08.006>.
- Lucena, J.J., Hernandez-Apaolaza, L., 2017. Iron nutrition in plants: an overview. *Plant Soil* 418, 1–4. <https://doi.org/10.1007/s11104-017-3316-8>.
- Ma, D., Yin, L., Ju, W., Li, X., Liu, X., Deng, X., Wang, S., 2021. Meta-analysis of green manure effects on soil properties and crop yield in northern China. *Field Crops Res.* 266, 108146 <https://doi.org/10.1016/j.fcr.2021.108146>.
- Mann, M., Kruger, J.E., Andari, F., McElean, J., Gascooke, J.R., Smith, J.A., Worthington, M.J.H., McKinley, C.C.C., Campbell, J.A., Lewis, D.A., Hasell, T., Perkins, M.V., Chalker, J.M., 2019. Sulfur polymer composites as controlled-release fertilisers. Electronic supplementary information (ESI) available: full experimental details including composite synthesis and characterisation, nutrient release studies, and tomato growth experiments. See D. Org. *Biomol. Chem.* 17, 1929–1936. <https://doi.org/10.1039/c8ob02130a>.
- Masunaga, T., Marques, F.J.D., 2018. Strategies for increasing micronutrient availability in soil for plant uptake. *Plant Micronutrient Use Efficiency: Molecular and Genomic Perspectives in Crop Plants.* Elsevier Inc. <https://doi.org/10.1016/B978-0-12-812104-7.00013-7>.
- Mattson, N.S., Iersel, M.W.Van, 2011. Application of the “4R” nutrient stewardship concept to horticultural crops: applying nutrients at the “Right Time.”. *Am. Soc. Hortic. Crops* 21, 667–673.
- Mazhar, M.W., Ishtiaq, M., Maqbool, M., Akram, R., 2022. Seed priming with Calcium oxide nanoparticles improves germination, biomass, antioxidant defence and yield traits of canola plants under drought stress. *South Afr. J. Bot.* 151, 889–899. <https://doi.org/10.1016/j.sajb.2022.11.017>.
- Mikkelsen, R., 2011. The “4R” nutrient stewardship framework for horticulture. *Am. Soc. Hortic. Crops* 21, 658–663.
- Miner, G.L., Delgado, J.A., Ippolito, J.A., Barbarick, K.A., Stewart, C.E., Manter, D.K., Del Grosso, S.J., Halvorson, A.D., Floyd, B.A., D’Adamo, R.E., 2018. Influence of long-term nitrogen fertilization on crop and soil micronutrients in a no-till maize cropping system. *Field Crops Res.* 228 (August), 170–182. <https://doi.org/10.1016/j.fcr.2018.08.017>.
- Mishra, S., Lin, Z., Pang, S., Zhang, Y., Bhatt, P., Chen, S., 2021. Biosurfactant is a powerful tool for the bioremediation of heavy metals from contaminated soils. *J. Hazard. Mater.* 418, 126253 <https://doi.org/10.1016/j.jhazmat.2021.126253>.
- Momesso, L., Alexandre, C., Crusciol, C., Cantarella, H., Sueko, K., Kowalchuk, G.A., Eurya, E., 2022. Optimizing cover crop and fertilizer timing for high maize yield and nitrogen cycle control. *Geoderma* 405, 115423. <https://doi.org/10.1016/j.geoderma.2021.115423>.
- Mucheru-Muna, M., Mugendi, D., Kung’u, J., Mugwe, J., Batiano, A., 2007. Effects of organic and mineral fertilizer inputs on maize yield and soil chemical properties in a maize cropping system in Meru South District, Kenya. *Agrofor. Syst.* 69, 189–197. <https://doi.org/10.1007/s10457-006-9027-4>.
- Mucheru-Muna, M.W., Ada, M.A., Mugwe, J.N., Mairura, F.S., Mugi-Ngenga, E., Zingore, S., Mutegi, J.K., 2021. Socio-economic predictors, soil fertility knowledge domains and strategies for sustainable maize intensification in Embu County, Kenya. *Heliyon* 7, e06345. <https://doi.org/10.1016/j.heliyon.2021.e06345>.
- Mudd, G.M., Jowitz, S.M., Werner, T.T., 2017. The world’s lead-zinc mineral resources: scarcity, data, issues and opportunities. *Ore Geol. Rev.* 80, 1160–1190. <https://doi.org/10.1016/j.oregeorev.2016.08.010>.
- Mugwe, B.J., Mugendi, D., Mucheru-muna, M., Merckx, R., Chianu, J., Vanlauwe, B., 2009. Determinants of the decision to adopt integrated soil fertility management practices by smallholder farmers in the central highlands of Kenya. *Exp. Agric.* 45, 61–75. <https://doi.org/10.1017/S0014479708007072>.
- Muhammad, S.R., Parashuram, B., Xue-cheng, S., Muhammad, I., 2020. Molybdenum as an essential element for crops: an overview. *Biomed. J. Sci. Tech. Res.* 24, 20–35. <https://doi.org/10.26717/bjstr.2020.24.004104>.
- Munaro, D., Mazo, C.H., Bauer, C.M., da Silva Gomes, L., Teodoro, E.B., Mazzarino, L., da Rocha Veileirinho, M.B., Moura e Silva, S., Maraschin, M., 2024. A novel biostimulant from chitosan nanoparticles and microalgae-based protein hydrolysate: improving crop performance in tomato. *Sci. Hortic.* 323, 112491 <https://doi.org/10.1016/j.scienta.2023.112491>.
- Mustafa, S., Bhatti, H.N., Maqbool, M., Iqbal, M., 2021. Microalgae biosorption, bioaccumulation and biodegradation efficiency for the remediation of wastewater and carbon dioxide mitigation: prospects, challenges and opportunities. *J. Water Process Eng.* 41, 102009 <https://doi.org/10.1016/j.jwpe.2021.102009>.
- Nagarajan, D., Lee, D., Chen, C., Chang, J., 2020. Bioresource Technology Resource recovery from wastewaters using microalgae-based approaches : a circular bioeconomy perspective. *Bioresour. Technol.* 302, 122817 <https://doi.org/10.1016/j.biortech.2020.122817>.
- Nduwumuremyi, A., Ruganzu, V., Mugwe, J.N., Rusanganwa, A.C., 2013. Effects of unburned lime on soil pH and base cations in acidic soil. *Hindawi* 2013, 23–35.
- Olorunfemi, D.I., Lolodi, O., 2011. Effect of cassava processing effluents on antioxidant enzyme activities in *Allium Cepa* L. *Biokemistri* 23 (2), 49–61.

- Ongheng, D., Muyanja, C., Ryckeboer, J., Geeraerd, A.H., Springael, D., 2011. Rhizosphere effect on survival of *Escherichia coli* O157 : H7 and *Salmonella enterica* serovar Typhimurium in manure-amended soil during cabbage (*Brassica oleracea*) cultivation under tropical field conditions in. *Int. J. Food Microbiol.* 149, 133–142. <https://doi.org/10.1016/j.jfoodmicro.2011.06.009>.
- Otieno, E.O., Kiboi, M.N., Gian, N., Muriuki, A., Musafiri, C.M., Ngetich, F.K., 2021. Uptake of integrated soil fertility management technologies in heterogeneous smallholder farms in sub-humid tropics. *Environ. Challenges* 5, 100394. <https://doi.org/10.1016/j.envc.2021.100394>.
- Otieno, E.O., Mburu, D.M., Ngetich, F.K., Kiboi, M.N., Fliessbach, A., Lenga, F.K., 2023. Effects of different soil management strategies on fertility and crop productivity in acidic nitisols of Central Highlands of Kenya. *Environ. Challenges* 11, 100683. <https://doi.org/10.1016/j.envc.2023.100683>.
- Oumer, A.M., Diro, S., Taye, G., Mamo, T., Jaleta, M., 2023. Agricultural lime value chain efficiency for reducing soil acidity in Ethiopia. *Soil Secur.* 11, 100092 <https://doi.org/10.1016/j.soisec.2023.100092>.
- Pandian, K., 2019. Potassium and secondary nutrients. *Int. J. Chem. Stud.* 7, 683–688. P-ISSN.
- Peters, J.B., Kelling, A., Schulte, E.E., 1996. Choosing between liming materials. *Extension* 4, 3–6.
- Płociniczak, M.P., Plaza, G.A., Piotrowska-Seget, Z., 2011. Environmental applications of biosurfactants: recent advances. *Int. J. Mol. Sci.* 633–654 <https://doi.org/10.3390/ijms12010633>.
- Popkin, B.M., Adair, L.S., Ng, S.W., 2011. Global nutrition transition and the pandemic of obesity in developing countries. *Nutr. Rev.* 70, 3–21. <https://doi.org/10.1111/j.1753-4887.2011.00456.x>.
- Rengel, Z., Batten, G.D., Crowley, D.E., 1999. Agronomic approaches for improving the micronutrient density in edible portions of field crops. *Field Crops Res.* 60, 27–40. [https://doi.org/10.1016/S0378-4290\(98\)00131-2](https://doi.org/10.1016/S0378-4290(98)00131-2).
- Renuka, N., Gulthe, A., Prasanna, R., Singh, P., Bux, F., 2018. Microalgae as multi-functional options in modern agriculture : current trends, prospects and challenges. *Biotechnol. Adv.* 36, 1255–1273. <https://doi.org/10.1016/j.biotechadv.2018.04.004>.
- Renuka, N., Prasanna, R., Sood, A., Bansal, R., Bidyarani, N., Shivay, Y.S., Nain, L., Amrik, S., 2017. Wastewater grown microalgal biomass as inoculants for improving micronutrient availability in wheat. *Rhizosphere* 30, 23–45. <https://doi.org/10.1016/j.rhisph.2017.04.005>.
- Romaniuk, R., Beltrán, M., Brutti, L., Costantini, A., Bacigaluppo, S., Sainz-Rozas, H., Salvaggiotti, F., 2018. Soil organic carbon, macro- and micronutrient changes in soil fractions with different lability in response to crop intensification. *Soil Tillage Res.* 181 (April), 136–143. <https://doi.org/10.1016/j.still.2018.04.014>.
- Rosales, M.A., Franco-Navarro, J.D., Peinado-Torrobá, P., Díaz-Rueda, P., Álvarez, R., Colmenero-Flores, J.M., 2020. Chloride improves nitrate utilization and NUE in plants. *Front. Plant Sci.* 11, 1–13. <https://doi.org/10.3389/fpls.2020.00442>.
- Roy, S., 1968. Mineralogy of the different genetic types of manganese deposits. *Econ. Geol.* 63, 760–786. <https://doi.org/10.2113/gsecongeo.63.7.760>.
- Saldanha, R.B., da Rocha, C.G., Caicedo, A.M.L., Consoli, N.C., 2021. Technical and environmental performance of eggshell lime for soil stabilization. *Constr. Build. Mater.* 298, 123648 <https://doi.org/10.1016/j.conbuildmat.2021.123648>.
- Sátiro, J.N.de O., Motta, A.C.V., Demetrio, W.C., Segalla, R.F., Cremonesi, M.V., Araújo, E.M., Falcão, N.P.de S., Martins, G.C., Muniz, A.W., Taube, P.S., Rebello, L., de Oliveira Júnior, R.C., Teixeira, W.G., Neves, E.G., Lima, H.P., Shock, M.P., Kille, P., Cunha, L., Network, T.P.L., Brown, G.G., 2021. Micronutrient availability in amazonian dark earths and adjacent soils. *Geoderma* 395 (5), 115072. <https://doi.org/10.1016/j.geoderma.2021.115072>.
- Scandinavia, A.A., Soil, S.B., Abate, E., Hussein, S., Laing, M., Mengistu, F., 2017. Soil acidity under multiple land-uses: assessment of perceived causes and indicators, and nutrient dynamics in small-holders' mixed-farming system of northwest Ethiopia. *Acta Agric. Scand. Sect. B* 67, 134–147. <https://doi.org/10.1080/09064710.2016.1230227>.
- Schwertmann, U., Fitzpatrick, R.W., 1992. Iron minerals in surface environments. *Catena Suppl.* 21, 7–30.
- Scipin, L., Scipin, D., Petukhova, V., Monakhova, Z., 2019. Efficiency of chemical ameliorants for reclamation of bore mud and solonchic soils of Siberia and Ural. In: *IOP Conference Series: Earth and Environmental Science*, 1. <https://doi.org/10.1088/1755-1315/337/1/012030>.
- Senthilkumar, K., Sillo, F.S., Rodenburg, J., Dimkpa, C., Saito, K., Dieng, I., Bindraban, P. S., 2021. Rice yield and economic response to micronutrient application in Tanzania. *Field Crops Res.* 270 (May), 108201 <https://doi.org/10.1016/j.fcr.2021.108201>.
- Serafim, B., Oginga, B., Njeri, J., 2013. Effects of manure, lime and mineral P fertilizer on soybean yields and soil fertility in a humic nitisol in the Central Highlands of Kenya. *Int. J. Agric. Sci. Res.* 2 (9), 283–291. <http://academeresearchjournals.org/journal/ijasr>.
- Shambhavi, S., Kumar, R., Sharma, S.P., Verma, G., Sharma, S.K., Sharma, R.P., 2018. Effect of 36 years of continuous cropping and fertilization on productivity, micro and secondary nutrient status and uptake by maize-wheat cropping system in Western Himalayas. *Int. J. Bio-Resource Stress Manage.* 9 (2), 197–202. <https://doi.org/10.23910/ijbsm/2018.9.2.1854b>.
- Sharma, R.P., Yadava, R.B., Lama, T.D., Bahadur, A., Singh, K.P., 2013. Status of secondary nutrients vis-a-vis soil site-characteristics of vegetable. *Veg. Sci.* 40, 65–68.
- Sharma, S., Dhaliwal, S.S., 2021. Conservation agriculture based practices enhanced micronutrients transformation in earthworm cast soil under rice-wheat cropping system. *Ecol. Eng.* 163 (25), 106195 <https://doi.org/10.1016/j.ecoleng.2021.106195>.
- Shukla, A.K., Behera, S.K., Pakhre, A., Chaudhari, S.K., 2018. Micronutrients in soils, plants, animals and Humans. *Indian Journal of Fertilisers* 14, 30–54. https://www.researchgate.net/profile/Arvind-Shukla-8/publication/324497356_Micronutrients_in_soils_plants_animals_and_humans/links/5c8c9b3092851c1df9446e79/Micronutrients-in-soils-plants-animals-and-humans.pdf%0Ahttps://www.researchgate.net/publication/32.
- Shukla, A., Srivastava, P., Tiwari, P., Prakash, C., Patra, A., Singh, P., Pachauri, S., 2015. Mapping current micronutrients deficiencies in soils of Uttarakhand for precise micronutrient management. *Indian J. Fertilisers* 11, 52–63.
- Shukla, K., Anshumali, 2018. Soil micronutrient pools and their transfer to paddy-crops in semi-arid agro-ecosystems, Central India. *Soil Tillage Res.* 180 (September 2017), 164–174. <https://doi.org/10.1016/j.still.2018.02.017>.
- Singh, R., Glick, B.R., Rathore, D., 2020. Role of textile effluent fertilization with biosurfactant to sustain soil quality and nutrient availability. *J. Environ. Manage.* 268, 110664 <https://doi.org/10.1016/j.jenvman.2020.110664>.
- Singh, R., Glick, B.R., Rathore, D., 2018. Biosurfactants as a biological tool to increase micronutrient availability in soil: a review. *Pedosphere* 28 (2), 170–189. [https://doi.org/10.1016/S1002-0160\(18\)60018-9](https://doi.org/10.1016/S1002-0160(18)60018-9).
- Singh, R.K., Chauhan, R., Kumar, R., 2021. An investigation on the effect of lime addition on UCS of Indian black cotton soil. *Mater. Today Proc.* 123, 11235. <https://doi.org/10.1016/j.matpr.2021.05.586>.
- Singh, R., Rathore, D., 2019. Ecotoxicology and Environmental Safety Impact assessment of azulene and chromium on growth and metabolites of wheat and chilli cultivars under biosurfactant augmentation. *Ecotoxicol. Environ. Saf.* 186 (June), 109789 <https://doi.org/10.1016/j.ecoenv.2019.109789>.
- Skórzyńska-Polit, E., Tukendorf, A., Selstam, E., Baszyński, T., 1998. Calcium modifies Cd effect on runner bean plants. *Environ. Exp. Bot.* 40, 275–286. [https://doi.org/10.1016/S0098-8472\(98\)00045-8](https://doi.org/10.1016/S0098-8472(98)00045-8).
- Somers, M.H., Azman, S., Bollansée, G., Goedemé, T., Leermakers, M., Alonso-Fariñas, B., Appels, L., 2020. Behavior of trace elements and micronutrients in manure digestate during ozone treatment. *Chemosphere* 252. <https://doi.org/10.1016/j.chemosphere.2020.126477>.
- Song, W., Shu, A., Liu, J., Shi, W., Li, M., Zhang, W., Li, Z., Liu, G., Yuan, F., Zhang, S., Liu, Z., Gao, Z., 2022. Effects of long-term fertilization with different substitution ratios of organic fertilizer on paddy soil. *Pedosphere* 32, 637–648. [https://doi.org/10.1016/S1002-0160\(21\)60047-4](https://doi.org/10.1016/S1002-0160(21)60047-4).
- Song, Y., Lin, Z., 2014. Abundance and community composition of ammonia-oxidizers in paddy soil at different nitrogen fertilizer rates. *J. Integr. Agric.* 13 (4), 870–880. [https://doi.org/10.1016/S2095-3119\(13\)60426-8](https://doi.org/10.1016/S2095-3119(13)60426-8).
- Spinelli, D., Bardi, L., Fierro, A., Jez, S., Basosi, R., 2013. Environmental analysis of sun flower production with different forms of mineral nitrogen fertilizers. *J. Environ. Manage.* 129, 302–308. <https://doi.org/10.1016/j.jenvman.2013.07.029>.
- Stanton, C., Sanders, D., Krämer, U., Podar, D., 2022. Zinc in plants: integrating homeostasis and biofortification. *Mol. Plant* 15, 65–85. <https://doi.org/10.1016/j.molp.2021.12.008>.
- Štofečková, L., Fazekas, J., Fazekášová, D., 2021. Analysis of heavy metal content in soil and plants in the dumping ground of magnesite mining factory jelsava-lubenfk (Slovakia). *Sustainability (Switzerland)* 13, 21. <https://doi.org/10.3390/su13084508>.
- Sun, G., Zeng, Q., Zhou, L., Wang, Y., Chen, P., 2020. Trace element contents and in situ sulfur isotope analyses of pyrite in the Baiyun gold deposit, NE China: implication for the genesis of intrusion-related gold deposits. *Ore Geol. Rev.* 118, 103330 <https://doi.org/10.1016/j.oregeorev.2020.103330>.
- Survey, B.G. (2008). *Definition, mineralogy and deposits* (Issue September), pp. 5–10.
- Svanbäck, A., Ulén, B., Etana, A., 2014. Mitigation of phosphorus leaching losses via subsurface drains from a cracking marine clay soil. *Agric. Ecosyst. Environ.* 184, 124–134. <https://doi.org/10.1016/j.agee.2013.11.017>.
- Syers, K., Johnston, E., Curtin, D., 2010. In: *19th World Congress of Soil Science Division Symposium 3. 2 Nutrient best management practices Table of Contents*, pp. 1–345 (Issue August).
- Syu, C.H., Yu, C.H., Lee, D.Y., 2020. Effect of applying calcium peroxide on the accumulation of arsenic in rice plants grown in arsenic-elevated paddy soils. *Environ. Pollut.* 266, 115140 <https://doi.org/10.1016/j.envpol.2020.115140>.
- Tabelin, C.B., Igarashi, T., Villacorte-Tabelin, M., Park, I., Opiso, E.M., Ito, M., Hironoshi, N., 2018. Arsenic, selenium, boron, lead, cadmium, copper, and zinc in naturally contaminated rocks: a review of their sources, modes of enrichment, mechanisms of release, and mitigation strategies. *Sci. Total Environ.* 645, 1522–1553. <https://doi.org/10.1016/j.scitotenv.2018.07.103>.
- Tang, Y., Wang, R., Tan, L., Guo, L., Duan, Y., Yang, L., Jiang, S., Zhou, F., Jiang, S., Huang, J., 2020. Effects of live microalgae and algae powder on microbial community, survival, metamorphosis and digestive enzyme activity of *Penaeus monodon* larvae at different growth stages. *Aquaculture* 526 (April), 735344. <https://doi.org/10.1016/j.aquaculture.2020.735344>.
- Taylor, P., Ulén, B., Etana, A., 2014. Phosphorus leaching from clay soils can be counteracted by structure liming. *Acta Agric. Scand. B* 37–41. <https://doi.org/10.1080/09064710.2014.920043>.
- Thirumurugan, D., Kokila, D., Balaji, T., Rajamohan, R., AlSalhi, M.S., Devanesan, S., Rajasekar, A., Parthipan, P., 2023. Impact of biosurfactant produced by *Bacillus* spp. on biodegradation efficiency of crude oil and anthracene. *Chemosphere* 344, 140340. <https://doi.org/10.1016/j.chemosphere.2023.140340>.
- Toksöz Hozatlıoğlu, D., Yılmaz, I., 2021. Shallow mixing and column performances of lime, fly ash and gypsum on the stabilization of swelling soils. *Eng. Geol.* 280, 105931 <https://doi.org/10.1016/j.enggeo.2020.105931>.
- Trejo, A., Luz, E., Hartmann, A., Hernandez, J., Rothballer, M., Schmid, M., Bashan, Y., 2012. Recycling waste debris of immobilized microalgae and plant growth-promoting bacteria from wastewater treatment as a resource to improve fertility of

- eroded desert soil. *Environ. Exp. Bot.* 75, 65–73. <https://doi.org/10.1016/j.envexpbot.2011.08.007>.
- Trumbull, R.B., Slack, J.F., 2018. Boron isotopes in the continental crust: granites, pegmatites, felsic volcanic rocks, and related ore deposits. *Adv. Isotope Geochem.* 249–272. https://doi.org/10.1007/978-3-319-64666-4_10.
- Vaishnavi, J., Devanesan, S., Alsalmi, M.S., Rajasekar, A., Selvi, A., Srinivasan, P., Govarthanan, M., 2021. Chemosphere Biosurfactant mediated bioelectrokinetic remediation of diesel contaminated environment. *Chemosphere* 264, 128377. <https://doi.org/10.1016/j.chemosphere.2020.128377>.
- Vanlauwe, B., Descheemaeker, K., Giller, K.E., Huisman, J., Merckx, R., Nziyheba, G., Wendt, J., Zingore, S., 2015. Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation. *Soil* 1, 491–508. <https://doi.org/10.5194/soil-1-491-2015>.
- Vanlauwe, B., Titttonell, P., Mukalama, J., 2006. Within-farm soil fertility gradients affect response of maize to fertilizer application in western Kenya. *Nutr. Cycling Agroecosyst.* 76 (2–3), 171–182. <https://doi.org/10.1007/s10705-005-8314-1>.
- Vollmer-Sanders, C., Allman, A., Busdeker, D., Moody, L.B., Stanley, W.G., 2016. Building partnerships to scale up conservation: 4R nutrient stewardship certification program in the Lake Erie watershed. *J. Great Lakes Res.* 42 (6), 1395–1402. <https://doi.org/10.1016/j.jglr.2016.09.004>.
- Wang, R., Dungait, J.A.J., Buss, H.L., Yang, S., Zhang, Y., Xu, Z., Jiang, Y., 2017. Base cations and micronutrients in soil aggregates as affected by enhanced nitrogen and water inputs in a semi-arid steppe grassland. *Sci. Total Environ.* 575 (8), 564–572. <https://doi.org/10.1016/j.scitotenv.2016.09.018>.
- White, P.J., Broadley, M.R., 2003. Calcium in plants. *Ann. Bot.* 92, 487–511. <https://doi.org/10.1093/aob/mcg164>.
- Wilson, M., 2004. Weathering of the primary rock-forming minerals: processes, products and rates. *Clay Miner.* 39, 233–266. <https://doi.org/10.1180/0009855043930133>.
- Wilson, M., Wilson, D.L., Mathur, R., 2016. Tracing the source of native copper mineral specimens with copper isotope values. *Rocks Miner.* 91, 352–356. <https://doi.org/10.1080/00357529.2016.1172176>.
- Wu, Y., Sun, M., Liu, J., Wang, W., Liu, S., 2019. Fertilizer and soil nitrogen utilization of pear trees as affected by the timing of split fertilizer application in rain-fed orchard. *Sci. Hortic.* 252 (12), 363–369. <https://doi.org/10.1016/j.scienta.2019.04.005>.
- Wuang, S.C., Khin, M.C., Qiang, P., Chua, D., Luo, Y.D., 2016. Use of Spirulina biomass produced from treatment of aquaculture wastewater as agricultural fertilizers. *Algal Res.* 15, 59–64. <https://doi.org/10.1016/j.algal.2016.02.009>.
- Yan, P., Shen, C., Zou, Z., Fu, J., Li, X., Zhang, L., Zhang, L., Han, W., Fan, L., 2021. Biochar stimulates tea growth by improving nutrients in acidic soil. *Sci. Hortic.* 283 (10), 110078. <https://doi.org/10.1016/j.scienta.2021.110078>.
- Yeboah, S., Asibuo, J., Oteng-Darko, P., Asamoah Adjei, E., Lamptey, M., Owusu Danquah, E., Waswa, B., Butare, L., 2021. Impact of foliar application of zinc and magnesium aminochelate on bean physiology and productivity in Ghana. *Int. J. Agron.* 2021, 2–20. <https://doi.org/10.1155/2021/9766709>.
- Yermiyahu, U., Zipori, I., Faingold, I., Yusopov, L., Faust, N., Bar-Tal, A., 2017. Polyhalite as a multi nutrient fertilizer-potassium, magnesium, calcium and sulfate. *Isr. J. Plant Sci.* 64, 145–157. <https://doi.org/10.1163/22238980-06401001>.
- Yin, C., Schlatter, D.C., Kroese, D.R., Paulitz, T.C., Hagerty, C.H., 2021. Impacts of lime application on soil bacterial microbiome in dryland wheat soil in the Pacific Northwest. *Appl. Soil Ecol.* 168, 104113. <https://doi.org/10.1016/j.apsoil.2021.104113>.
- Yousaf, M., Bashir, S., Raza, H., Shah, A.N., Iqbal, J., Arif, M., Bukhari, M.A., Muhammad, S., Hashim, S., Alkahtani, J., Alwahibi, M.S., Hu, C., 2021. Role of nitrogen and magnesium for growth, yield and nutritional quality of radish. *Saudi J. Biol. Sci.* 28, 3021–3030. <https://doi.org/10.1016/j.sjbs.2021.02.043>.
- Yruela, I., 2005. Copper in plants. *Braz. J. Plant Physiol.* 17, 145–156. <https://doi.org/10.1590/s1677-04202005000100012>.
- Zambrano, G.F., Souza, A.D., Zucareli, C., Sarkis, Y.J., Rodrigues, S.H., Hélder, H.E., Maddela, N.R., Sánchez-Urdaneta, A.B., Guimarães, M., de F., Prasad, R., 2023. Combination effects of microbial inoculation and N fertilization on maize yield: a field study from southern Brazil. *Rhizosphere* 27, 100768. <https://doi.org/10.1016/j.rhisph.2023.100768>.
- Zhou, W., Han, G., Liu, M., Li, X., 2019. Effects of soil pH and texture on soil carbon and nitrogen in soil pro fi les under different land uses in Mun River Basin, Northeast Thailand. *PeerJ* 23, 334–345. <https://doi.org/10.7717/peerj.7880>.
- Zohra, F., Mnif, S., Badis, A., Rebbani, S., 2014. Naphthalene and crude oil degradation by biosurfactant producing *Streptomyces* spp. isolated from Mitidja plain soil (North of Algeria). *Int. Biodeterior. Biodegrad.* 86, 300–308. <https://doi.org/10.1016/j.ibiod.2013.10.003>.