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A comprehensive review on nano-fertilizers: preparation, development, utilization, and prospects for sustainable agriculture in Ethiopia

Eyasu Derbew Demeke,[a] Natei Ermias Benti,[c] Mintesnot Gizaw Terefe,[d] Teshome Taye Anbessa,[b] Wondimagegne Mamo Mengistu*[b] and Yedilfana Setarge Mekonnen*[a]

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With their many benefits including better crop yield and nutrient delivery, nano fertilizers are a promising option in the agriculture sector. The production and formulation of nanoparticles with regulated size, shape, and content are required to prepare nano fertilizers. Metals, metal oxides, and polymers are among the materials from which nanoparticles are made using chemical and physical processes. Subsequently, these nanoparticles are mixed into fertilizers to enhance plant absorption and availability of nutrients. Nano-fertilizers have several benefits, including efficient nutrient absorption, reduced nutrient losses, minimized environmental pollution, optimized resource utilization, and controlled release of nutrients for sustained plant nourishment. Studies have demonstrated that by boosting nutrient availability, encouraging root development, and strengthening stress tolerance, nano fertilizers can greatly enhance crop yields. Moreover, it has been discovered that they increase microbial activity and soil fertility, which improves soil health and long-term sustainability. Nano-fertilizers can be applied in different ways, like foliar spraying, seed coating, soil integration, or irrigation systems. They are beneficial in precision agriculture for better nutrient management, soil restoration, and addressing nutrient deficiencies. Furthermore, they potentially lessen the negative environmental effects of traditional fertilization methods. Nevertheless, there are still several issues that need to be resolved before nano fertilizers may be commercialized and widely used. Regulatory frameworks, environmental destiny, potential toxicity of nanoparticles, and cost-effectiveness are some of these challenges. The purpose of this review is to provide readers with a comprehensive understanding of the benefits of nano fertilizers. It will cover topics such as their preparation and characterization, potential side effects, and a diverse range of applications. Additionally, it will present an overview of the importation of chemical fertilizers and explore the prospects of utilizing fertilizers in the Ethiopian context.

1. Introduction

Agriculture is the cornerstone of Ethiopia's economy, accounting for a substantial portion of its GDP and serving as the primary livelihood for a majority of its population (Fig. 1). Smallholder farms, typically less than two hectares in size and operated by family members, are the dominant form of agriculture in Ethiopia. These farms produce over 95% of the country's main crops, including cereals, pulses, oilseeds, vegetables, and fruits.[1–3] However, smallholder farmers face various challenges that hinder increased agricultural output, such as limited access to quality inputs like seeds and fertilizers, land degradation, economic constraints, and a heavy reliance on rainfall.

As the global population continues to grow, the need to enhance agricultural productivity while minimizing environmental impact is becoming increasingly critical.[4] Conventional fertilizers, though widely used to boost crop yields, have significant drawbacks. Excessive application can lead to heavy metal contamination of soil and water, posing serious risks to human health and causing environmental damage like soil erosion and eutrophication.[5–7] In this context, nano-fertilizers have emerged as a promising alternative with the potential to revolutionize agricultural practices. Nano-fertilizers utilize nanomaterials for enhanced nutrient delivery and uptake, offering several advantages over conventional fertilizers. These include increased nutrient use efficiency, reduced nutrient loss,

[a]Center for Environmental Science, College of Natural and Computational Sciences, Addis Ababa University, P. O. Box 1176, Addis Ababa, Ethiopia. E-mail: yedilfana.setarge@aau.edu.et
[b]Bio and Emerging Technology Institute, Nanotechnology Directorate, P. O. Box 5954, Addis Ababa, Ethiopia. E-mail: wondima2002@gmail.com
[c]Computational Data Science, College of Natural and Computational Sciences, Addis Ababa University, P. O. Box 1176, Addis Ababa, Ethiopia
[d]Sustainable Energy Center of Excellence, Addis Ababa Science and Technology University, Addis Ababa, Ethiopia

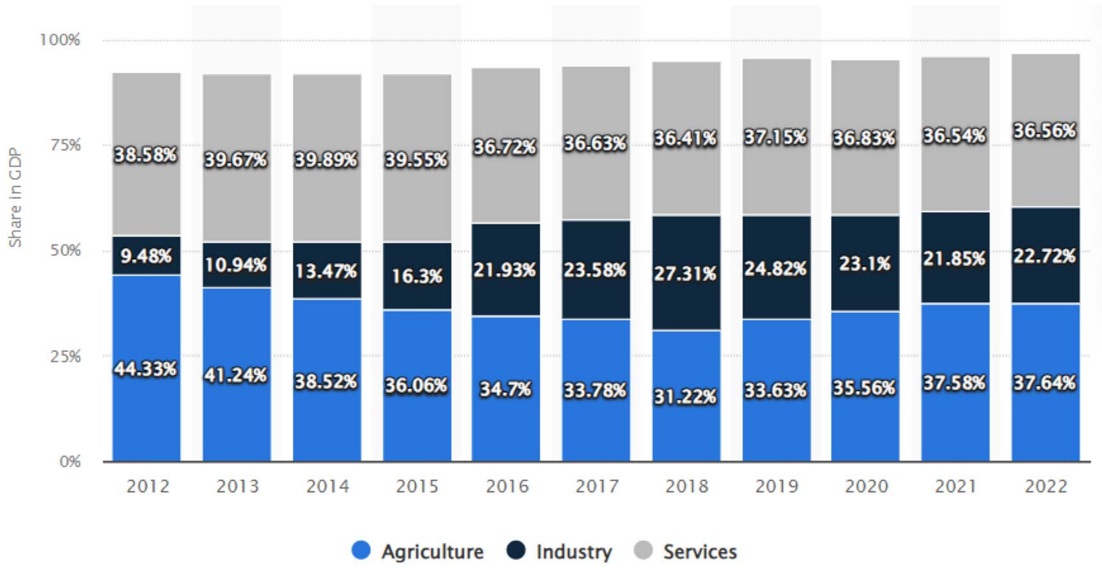

Fig. 1 Distribution of economic sectors in Ethiopia's GDP from 2012 to 2022.

minimized environmental pollution, and controlled release of nutrients for sustained plant nourishment.

This review provides a comprehensive overview of nano-fertilizers, encompassing their preparation, characterization, benefits, and diverse applications. It also explores the potential of nano-fertilizers to address the specific challenges faced by Ethiopian agriculture and contribute to sustainable farming practices in the country.

Nanomaterials are particles and materials that are handled at a nanoscale range of 1–100 nm. The unique characteristics of nanomaterials when paired with native and conventional methods could lead to a variety of innovative uses in a range of scientific fields, including agriculture, which needs creative approaches to guarantee global food security.[8] The idea of using nanotechnology in agriculture is not new; several reports that were published by the Department of Agriculture in the USA, nano-forum, and others have emphasized nanotechnology-based research and application in the agricultural sector.[9] Moreover, controlled release of pesticides, monitoring soil health, and plant nutrition are among the other uses of nano-structured systems in agriculture. This approach is a component of the rapidly developing field of precision agriculture, which works in combination with sustainable agriculture to lower energy consumption and waste production. In precision agriculture, farmers employ technology to make optimal use of inputs like water, fertilizer, and other resources.[10,11] Furthermore, enhancing crop quality and yield also heavily depends on the fertility and quality of the soil.[12] Encapsulated or coated in nanomaterial, nano-fertilizers allow for regulated release of nutrients and their gradual diffusion into the soil. Long-term

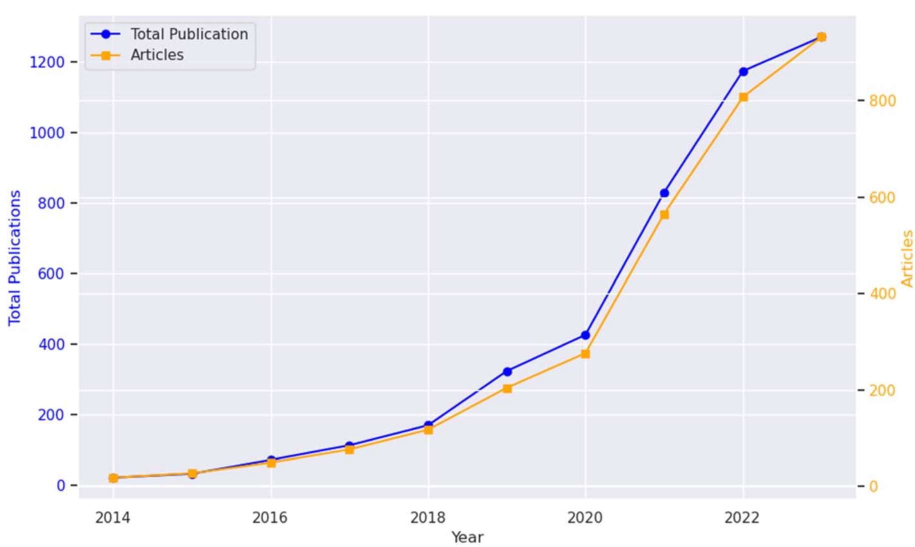

Fig. 2 Research and publication trends in nano fertilizer studies (2014–2023).

Table 1 Publications on nano-fertilizers in the last decade

Year	Publications	Citations	Article	Chapter	Book	Preprint	Proceeding	Monograph
2014	22	29	18	3	1	0	0	0
2015	33	91	27	3	1	1	1	0
2016	72	303	49	13	9	0	1	0
2017	113	612	76	20	14	0	1	2
2018	170	1211	117	33	18	0	1	1
2019	324	2677	204	80	34	2	1	3
2020	427	4626	276	103	41	3	3	1
2021	831	10 174	565	181	59	22	3	1
2022	1175	17 889	807	252	72	28	11	5
2023	1272	22 870	932	227	74	29	7	3
Total	4439	60 482	3071	915	323	85	29	16

improvement of the soil's fertility and nutrient quality as well as increased crop productivity can be achieved by using nanoscale fertilizers to minimize nutrient loss through leaching and run-off and to slow down the nutrients' rapid degradation and volatility.[13] Furthermore, nano-fertilizers have a high surface area to volume ratio and a high penetration ability, which makes them a viable substitute for chemical fertilizers. Additionally, using nano-fertilizers can significantly lessen environmental hazards. According to a number of studies, nano-fertilizers can increase crop output by encouraging stress tolerance, nitrogen metabolism, photosynthesis, protein and carbohydrate synthesis, and seed germination.[13]

The literature indicates that throughout the past decade, there have been notable advancements in the creation of nano-fertilizers for use in agriculture (Fig. 2). As of October 2023, 4439 publications have been published on the topics of "agriculture" and "Nano-fertilizers," according to the Web of Science database (Table 1). The exponential growth of research and publication efforts demonstrates that nano-fertilizers are the fertilizers of the future, ruling modern agriculture and offering strategic possibilities for future fertilizer development (Fig. 2). Nano-fertilizers have drawn attention for their potential to enhance agricultural productivity while preserving environmental quality through advanced nutrient delivery methods.

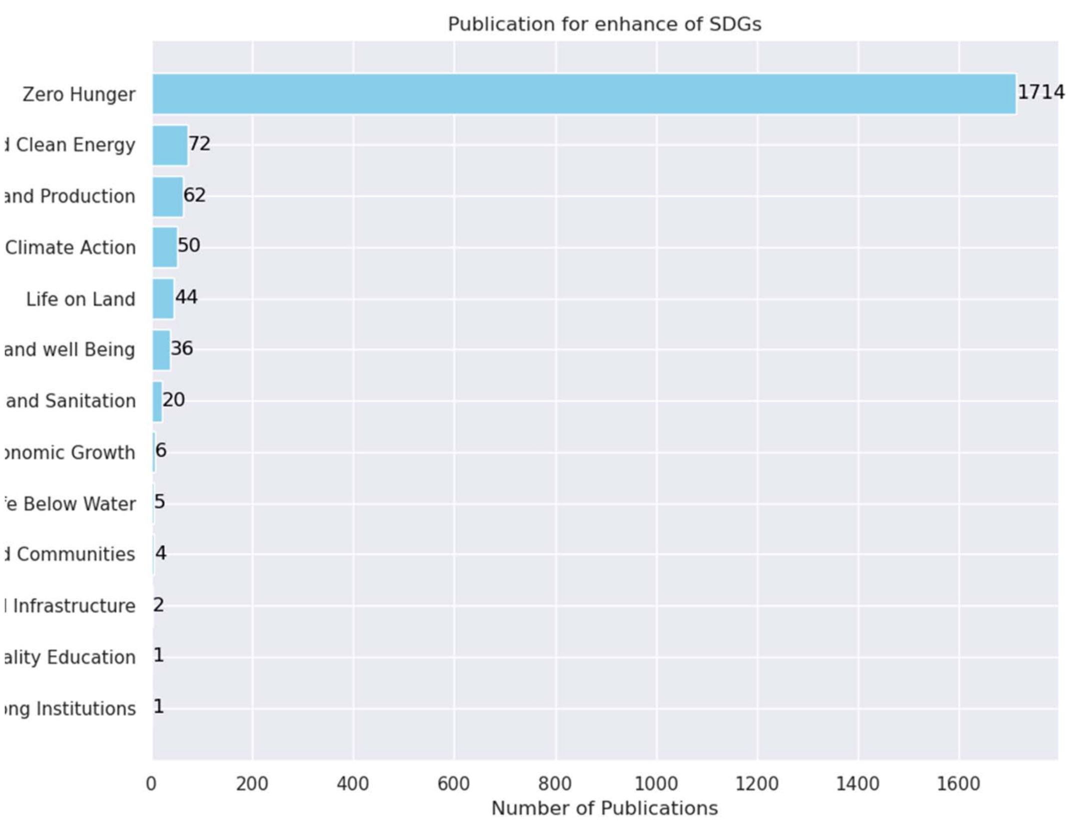

Fig. 3 Improving progress of publications toward sustainable development goals (SDG).

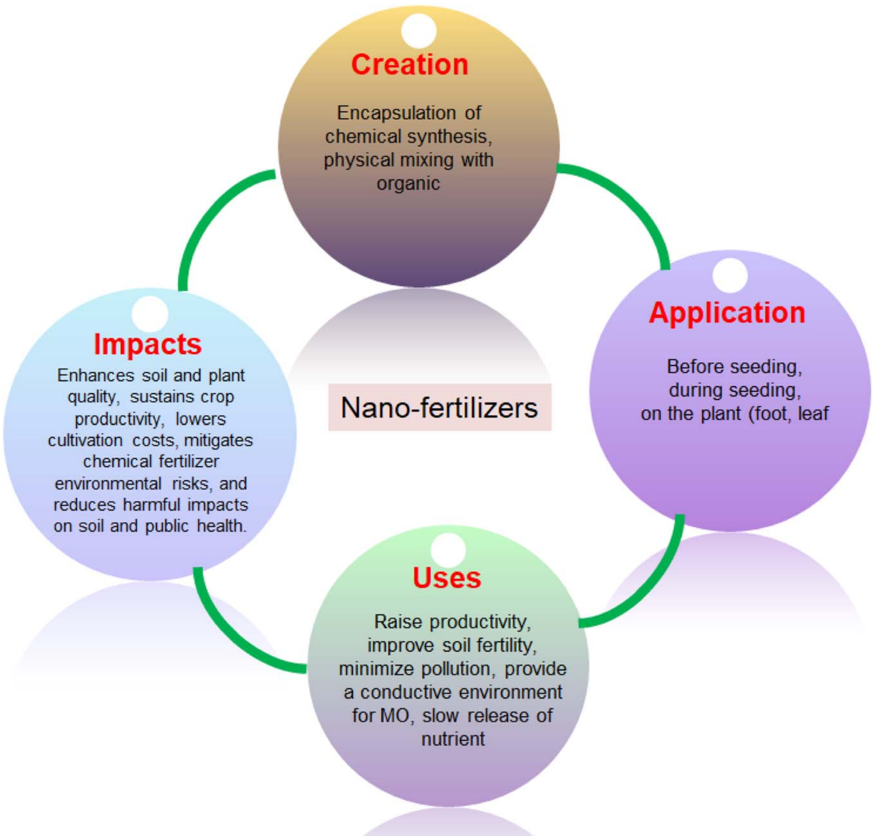

Fig. 4 Graphical representation of the review.

Additionally, it is greatly and quickly improving progress towards the sustainable development goals (SDG) of achieving zero hunger (Fig. 3).

Nanoparticles (NPs) are becoming increasingly used in agriculture. This review provides a fresh and improved viewpoint on the creation, application, consequences, and implications of nano fertilizers in environmental and agricultural fields. Current research on the use of nano fertilizers, their interactions with plants, and their consequences on humans and animals are also covered. A graphical representation of this review is shown in Fig. 4.

2. Preparation and development of nano fertilizer

The preparation of nano-fertilizers has its roots in a very interesting application of nanoparticles as 'smart' delivery systems and its effect on seed germination and plant growth rates. The development of carbon nanotubes as nano-transporters for intact plant cells paves the way for the creation of nano-fertilizers for agricultural use.[14,15]

The goal of recent advancements in the synthesis and formulation of nanoparticles for use in nano-fertilizers has been to produce particles with controlled dimensions, shapes, and contents. The goal of these developments is to improve fertilizers' efficacy and efficiency in stimulating plant growth and raising crop yields. The following are some significant advancements in the synthesis and composition of nanoparticles for nano fertilizers:[16] (a) regulate the size and form of the nanoparticles used in nano-fertilizers, researchers are looking into many different approaches. The nanoparticles can be made to interact with plants in certain ways by carefully adjusting these characteristics, which will enhance nutrient intake and overall plant performance.[17] (b) Safeguard nanoparticles and regulate their release into the soil, encapsulation approaches are being developed.[18] This maximizes fertilizer availability for plants and minimizes nutrient waste by enabling a controlled and continuous delivery of nutrients.[19,20] (c) Improves a nanoparticle's characteristics and interactions with plants, it can be functionalized with particular chemicals or substances. For instance, adding organic molecules to nanoparticles can enhance their stability, dispersibility, and capacity to transfer nutrients.[21] (d) Scientists are investigating methods for directing the delivery of nanoparticles to particular organs or tissues within plants. By ensuring that the nanoparticles reach the specified location of action, this tailored delivery technique maximizes their effectiveness and reduces any potential environmental effects.[12] (e) Provide synergistic effects, nano fertilizers can be mixed with other inputs like conventional fertilizers, bio-fertilizers, or plant growth regulators. These combinations can boost plant growth, improve nutrient uptake, and raise agricultural yields.[22] (f) Employing biodegradable

Table 2 Recently developed nano fertilizers and their applications

Nano-fertilizers	Application	Reference
Nanoscale iron oxide	Have been used to coat urea in nano fertilizers. This coating helps control water nutrient loss in soil	26
Slow-release phosphorus nano fertilizers	Nano-rock phosphate and nano-hydroxyapatite, have shown promising results in supplying phosphorus to plants throughout their life cycle, improving phosphorus utilization, and enhancing plant growth and yield	27
Ammonium sulfate nanoparticles	Provide plants with a readily available source of nitrogen and sulfur. These nutrients are essential for plant growth and development	28
Silicon dioxide nanoparticles ($nSiO_2$)	Improved canopy spread, stem diameter, plant height, and ground cover	29
Nano-porous zeolite-based nitrogen fertilizers	Have been used as an alternative strategy to improve nitrogen use efficiency in crop production systems	14
Copper nanoparticles	Enhance copper availability to plants. Copper is a micronutrient required for various plant metabolic processes	15
Zinc nanoparticles	Can improve zinc uptake by plants. Zinc is an important micronutrient for plant growth and development	16
Potassium nanoparticles	Improve potassium availability to plants. Potassium is a macronutrient required for various plant metabolic processes, higher absorption rates and are more resistant to leaching	17
Molybdenum nanoparticles	Can improve molybdenum uptake by plants. Molybdenum is an essential micronutrient for nitrogen fixation in leguminous plants	19
Boron nanoparticles	To enhance boron availability to plants. Boron is a micronutrient required for various plant physiological processes	20
Sulfur nanoparticles	They can be coated onto urea or other fertilizer compounds to improve nutrient release and reduce nutrient losses	21
Calcium nanoparticles	Enhance calcium availability to plants. This can improve plant growth and development enhancing plants' resistance to disease and pests	12 and 30
Magnesium nanoparticles	To provide plants with readily available magnesium. This micronutrient is essential for various physiological processes in plants	31

materials or minimizing the use of potentially hazardous compounds, researchers are also concentrating on creating ecologically acceptable nano-fertilizers. This guarantees that nano-fertilizers will benefit plants as intended with minimal negative impacts on the environment.[23]

Different researchers[24,25] developed various kinds of nano fertilizers based on availability and need, as indicated in Table 2. By increasing nutrient use efficiency, lowering nutrient losses in the soil, and lessening environmental effects, nano fertilizers, which use nanomaterials to boost nutrient uptake, have shown promise enhancing agricultural productivity. These are a few instances of nanomaterials that are frequently found in fertilizers and have been effectively applied to agriculture.

Nano-fertilizers are typically created by synthesizing or modifying nanoparticles to encapsulate or carry nutrients. These nanoparticles can be made from various materials such as metals, metal oxides, carbon-based materials, or polymers. The nanoparticles are often engineered to have specific properties, such as controlled release of nutrients, increased solubility, or targeted delivery to plant tissues.[32] Nano-fertilizers are designed to increase nutrient utilization efficiencies by utilizing the unique features of nanoparticles. To create nanomaterials, both physical (top-down) and chemical (bottom-up) techniques are utilized, and the targeted nutrients are loaded as they are for cationic nutrients (NH_4^+, K^+, Ca^{2+}, Mg^{2+}) and after surface modification for anionic nutrients (NO_3^{1-}, PO_4^{2-}, SO_4^{2-}). One of these new technologies is the encapsulation of fertilizers within a nanoparticle, which is done in three ways. The nutrient can be stored inside nano-porous materials, coated with a thin polymer layer, or given as nano-scale particles or emulsions.[33]

3. Preparation of nano fertilizer

Nutrient-containing nanoparticles are utilized in the production of nanoscale fertilizers, offering several advantages for plant growth. These nanoparticles can be synthesised using various methods, including physical (top-down), chemical (bottom-up), and biosynthesis approaches, as illustrated in Fig. 5. The use of these nanoparticles enhances nutrient delivery and uptake, thereby improving agricultural efficiency and sustainability.

3.1. Top-down methods

In a top-down approach, the bulk material is often broken down into its constituent nano-sized structures or particles. These methods are a development of those previously employed to create particles with a micron size. To obtain the nano dimension, this method requires substrates, such as zeolites or other materials, that are ball-ground for several hours, and the required nutrients are encapsulated.[34]

3.2. Bottom-up methods

The term "bottom-up approach" describes the process of building material atom by atom, molecule by molecule, or cluster by cluster from the bottom up. It indicates that NPs are

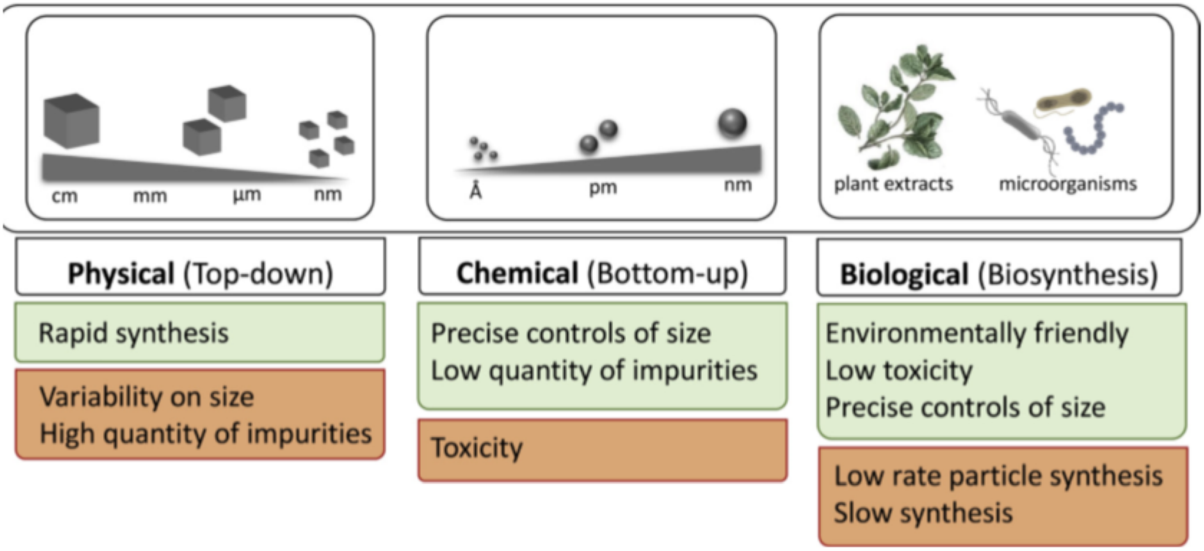

Fig. 5 Preparation of nano fertilizer using different methods.[37]

formed by a specific chemical reaction that begins with molecules in the solution and proceeds through molecule interaction.[35,36]

3.3. Biosynthesis: a greener way

Green synthesis is the process of creating NPs using straightforward, affordable, environmentally friendly, and effective technologies. Plant extracts, fungi, yeasts, bacteria, and algae are examples of natural sources that can be used to biologically synthesize metal and metal oxide nanoparticles (NPs).[38]

4. Benefits of nano fertilizers

Nano-fertilizers have the potential to transform nutrient management and offer several potential advantages in agriculture. The following are some of the main advantages of nano fertilizers: enhanced nutrient uptake and enhanced nutrient use efficiency: in agricultural systems, nano-fertilizers have great promise for enhancing and optimizing water and nutrient utilization efficiency.[26]

In contrast to traditional fertilizers, nutrients are bonded to nano-dimensional adsorbents, which release them gradually. Because of their nanoscale size, plant roots may absorb nutrients more effectively due to their larger surface area. Increased nutrient uptake has the potential to boost plant development, yield, and growth. With the help of nano fertilizers, plants may absorb nutrients more efficiently and make better use of the resources that are available to them, which lessens the need for over-fertilizer application and reduces wastage.[39] This feature helps promote sustainable agricultural methods and is especially helpful in areas with limited water resources. Moreover, controlled-release characteristics of nano fertilizers can be developed to guarantee a consistent and long-lasting supply of nutrients to plants. Farmers can apply lesser amounts of fertilizer and save money since this controlled-release feature decreases nutrient loss through leaching or volatilization and lowers the frequency of fertilizer application. Additionally, nano fertilizers can be engineered to target particular plant tissues or organs, such as seeds or leaves, and supply nutrients exactly where they are required. This customized distribution method lowers waste while increasing the effectiveness of nutrient consumption.

4.1 Increased crop yields and customized formulations

Higher crop yields may result from nano-fertilizers' increased nutrient utilization efficiency. Increased productivity can be achieved by using nano-fertilizers to support optimal plant growth and development through more efficient and targeted nutrient delivery. With the use of nano fertilizers, nutrient compositions can be tailored to the needs of individual crops and soil types. Farmers can better manage nutrient imbalances or shortages because of this flexibility, which enhances crop yield and health.[40]

4.2 Minimized environmental impact and possibility for precision farming

Farmers may apply nutrients more precisely and accurately thanks to the use of nano fertilizers, which are in line with the principles of precision agriculture. Farmers can improve nutrient distribution and avoid waste by focusing on certain areas or individual plants, leading to more resource-efficient and sustainable agricultural practices.[41]

Runoff and nutrient leakage into the environment can be lessened with the use of nano-fertilizers' precise distribution and controlled-release characteristics. This reduces the detrimental effects of fertilizers on ecosystems and water bodies, which lowers eutrophication and water pollution and is good for environmental sustainability. Furthermore, plants' efficient uptake and use of nutrients reduces the possibility of nutrient buildup in soil, which can be harmful to ecosystems.[42]

4.3 Compatibility with other agricultural inputs and stress tolerance

Multifunctional formulations can be created by simply integrating nano fertilizers with other agricultural inputs, such as growth regulators or insecticides. This compatibility minimizes the need for several applications while improving the convenience and effectiveness of agricultural methods. Additionally, plants' ability to withstand abiotic stress may be improved by nano-fertilizers. They can increase crop resilience and yield by assisting plants in adjusting to harsh environmental circumstances such as salt, drought, and heavy metal stress.[25]

4.4 Synergy with microorganisms

To produce nano-bio fertilizers, which have extra advantages, nano-fertilizers can be combined with microorganisms. These nano-bio fertilizers combine the advantageous properties of beneficial microbes with nano-technology to increase nutrient availability, encourage plant development, and improve soil health.[43] It is noteworthy that whereas nano-fertilizers present noteworthy benefits, it is imperative to meticulously evaluate their possible drawbacks and hazards before their extensive use. To ensure the safe and responsible use of nano-fertilizers in agriculture, more study is required. The release of nanomaterials into the environment and the food chain may pose concerns to human health.

5. Impact of nano-fertilizers

Sustainable agriculture could undergo a revolution with the use of non-toxic nano-fertilizers, which can boost crop yields while lessening their environmental impact. The possible effects that these fertilizers may have on the environment, human health, and society must be taken into account. The toxicity of nano fertilizers to people and animals is one possible worry. Certain nano-fertilizers, like nano zinc and nano titanium dioxide, have been shown in several studies to be harmful to aquatic life as well as human cells. To completely comprehend the possible negative impacts of nano fertilizers on the environment and human health, more research is required.[44,45]

The possibility of environmental pollution from nano-fertilizers is another aspect of their impact on the environment. Nano-fertilizers have the potential to contaminate soil and water bodies if they are not properly handled. Ecosystems and living things in the environment may suffer as a result.[46] There is a chance that nano fertilizers will build up in the food chain. If crops take up nanoparticles from nano fertilizers, animals or people who eat these crops may also be exposed to the nanoparticles. This prompts questions about how nano fertilizers can affect the food chain in the long run.[47] Many countries do not yet have regulations on nano fertilizers. The usage of these fertilizers may be hazardous, hence there are concerns over their safety due to the absence of regulation.[48] It is crucial to remember that additional study is required to completely comprehend the advantages and disadvantages of non-toxic nano fertilizers. To guarantee the fertilizers' sustainable and safe usage in agriculture, the scientific community is actively researching the effects these fertilizers have on the environment.[49]

6. Types of nano fertilizers

Nano-fertilizers are classed according to their composition and mechanism of action. Nano-sized nutrient particles, nano-coated fertilizers, nano-encapsulated fertilizers, and nano-composite fertilizers are some examples.[50] Each has its own set of characteristics and processes for nutrient delivery and release.

Nano-fertilizers are a form of fertilizer based on nanotechnology that uses nanoparticles to improve nutrient delivery and release in plants. They have various advantages over traditional fertilizers, including increased nutrient uptake efficiency, lower nutrient losses, and targeted nutrient release. Here are some examples of nano-fertilizers, along with their characteristics and nutrient delivery and release mechanisms: (1) nano encapsulated fertilizers consist of nano-sized capsules that encapsulate the nutrients. The capsules are usually made of biodegradable polymers or inorganic materials. The encapsulation protects the nutrients from degradation and leaching, allowing for controlled release. The release of nutrients from the capsules can be triggered by various factors such as soil moisture, temperature, or microbial activity.[25] (2) Nano-coated fertilizers involve coating the surface of conventional fertilizer particles with nanomaterials. The nano-coating provides a protective layer around the fertilizer particles, preventing nutrient loss through leaching or volatilization. The nano-coating can also control the release of nutrients by modulating the coating thickness or using pH-sensitive coatings that release nutrients in response to specific soil conditions.[51] (3) Nano-composite fertilizers are formed by incorporating nanoparticles directly into the fertilizer matrix, typically using nano clays or carbon nanotubes. The nanoparticles in the nanocomposite structure enhance nutrient retention and slow down nutrient release. They can also improve the water-holding capacity of the soil and promote microbial activity, leading to improved nutrient availability for plants.[52] (4) Nano-chelated fertilizers involve the use of nanoparticles to chelate or bind with specific nutrients, such as iron, zinc, or copper. The chelation process improves the stability and solubility of the nutrients, making them more available to plants. The nanoparticles can also protect the nutrients from chemical reactions in the soil, ensuring their efficient uptake by plant roots.[53]

Overall, nano-fertilizers offer the potential to improve nutrient use efficiency and reduce environmental impacts by providing more targeted and controlled nutrient delivery to plants. However, it's important to note that further research and development are needed to optimize their performance, assess their long-term effects on soil and plant health, and ensure their safe application in agriculture.

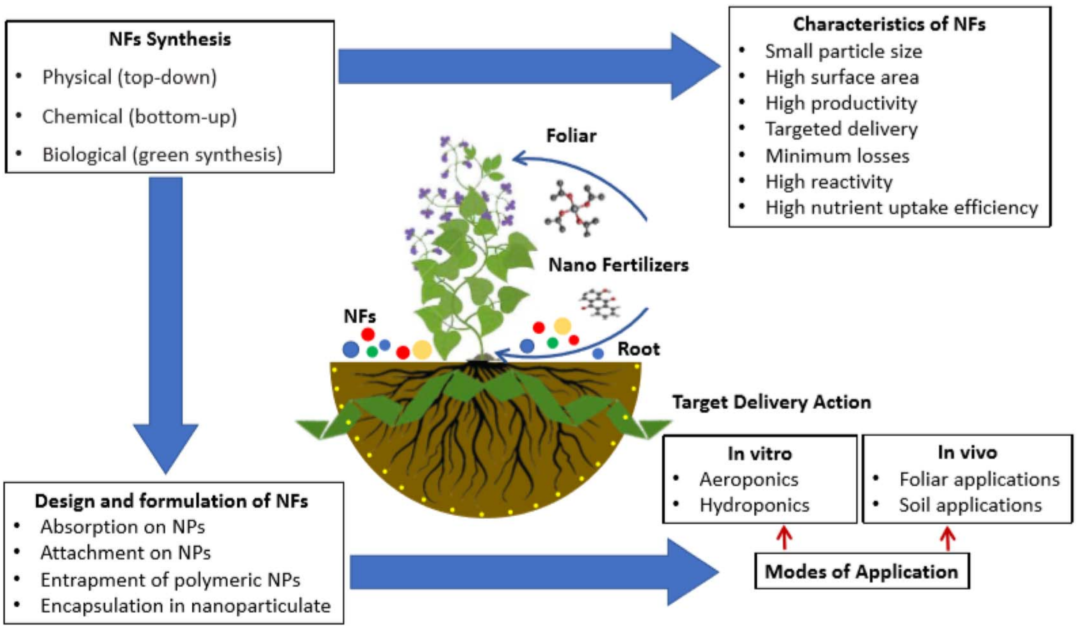

Fig. 6 Overview of design and formulation of nano fertilizers based on the respective preparation method and their characteristics.[56]

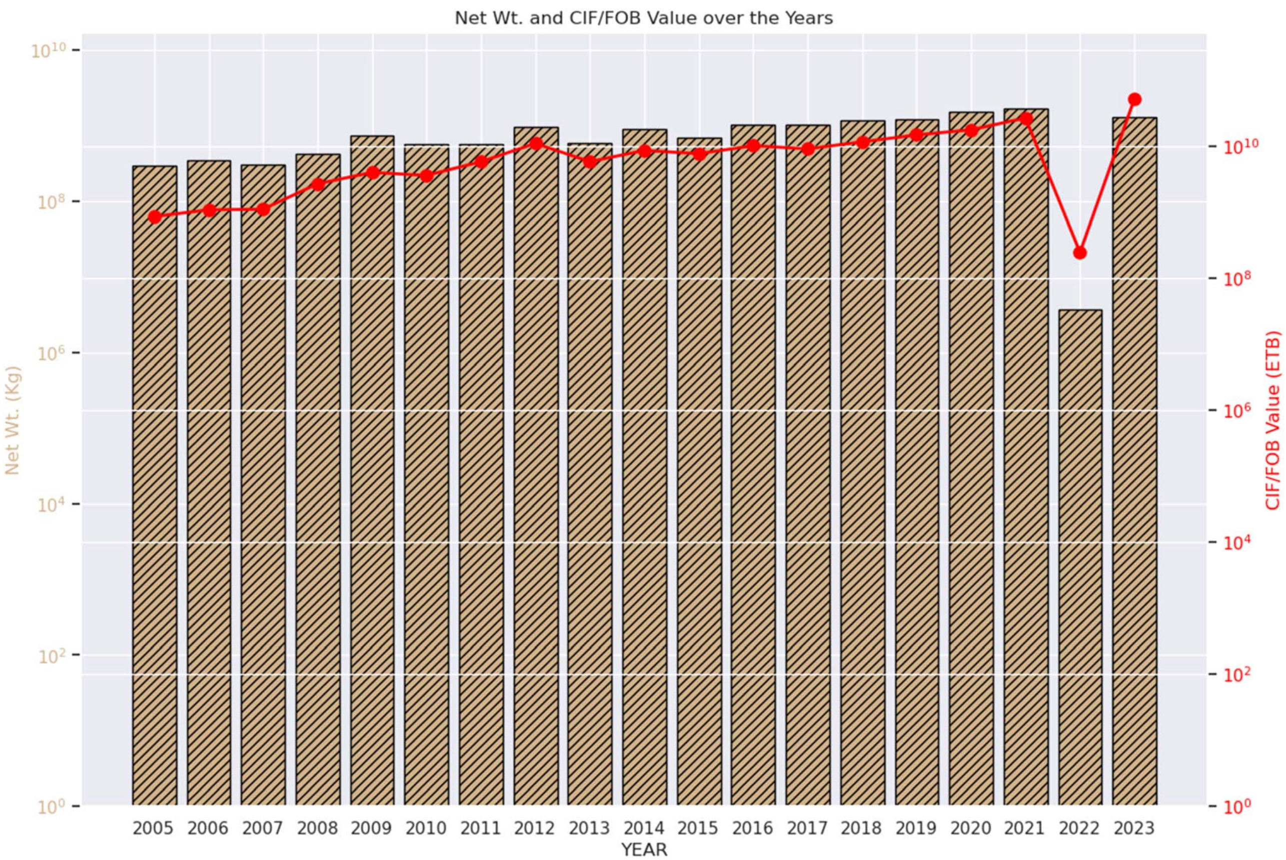

Fig. 7 Evolution of net weight and CIF/FOB value across the years. (CIF – Cost, insurance, and freight and FOB – free on board).

7. Uptake and movement of nanoparticles

Nanoparticles can enter a plant's system through a variety of channels, including the root, and shoot, even through wounds and root junctions.[33] The penetration of nanoparticles through the cell wall is greatly influenced by the pore diameter of the cell wall (5–20 nm).[54] Therefore, nanoparticles aggregate with a diameter smaller than the pore size of the plant cell wall could easily pass through the cell wall and reach the plasma membrane. As a result, one of the primary barriers to nanoparticle entry into the plant system is considered to be pore size.

Traditional fertilizers are commonly applied through conventional methods such as broadcasting or side-dressing. However, nano-fertilizers may require specialized application techniques to ensure proper distribution and uptake. For example, precision application methods such as foliar spraying or seed coating may be more suitable for nano-fertilizers to target specific plant tissues or root zones. Nano-fertilizers may require precise application techniques such as foliar spraying. Specialized spraying equipment, such as precision sprayers or sprayers with adjustable nozzles, can help ensure uniform coverage and targeted delivery of nano-fertilizers to plant leaves. These sprayers are designed to produce fine droplets for optimal absorption and minimize drift.[37]

Different crops have unique nutrient requirements and growth characteristics. Nano-fertilizers can be tailored to specific crops, taking into account their nutritional needs, growth stages, and environmental conditions. Crop-specific formulations optimize nutrient delivery and uptake, resulting in improved crop performance and yield.[55] Adjustments in dosage and timing of fertilizer application may be necessary when using nano-fertilizers. The optimal dosage and timing of nano-fertilizer application may differ from traditional fertilizers due to their controlled-release properties and enhanced nutrient uptake efficiency. Precision in determining the appropriate dosage and timing can help maximize the benefits of nano-fertilizers and minimize any potential adverse effects (Fig. 6).[57]

8. Systems for decision support and data management

Incorporating nano-fertilizers with other agricultural technology can improve crop yield and sustainability in general. The effectiveness of nano-fertilizers can be increased by integrating them with data management and decision support systems.[58] Through this integration, resource efficiency is increased, environmental consequences are decreased, and more accurate and focused nutrient management is made possible. Precision

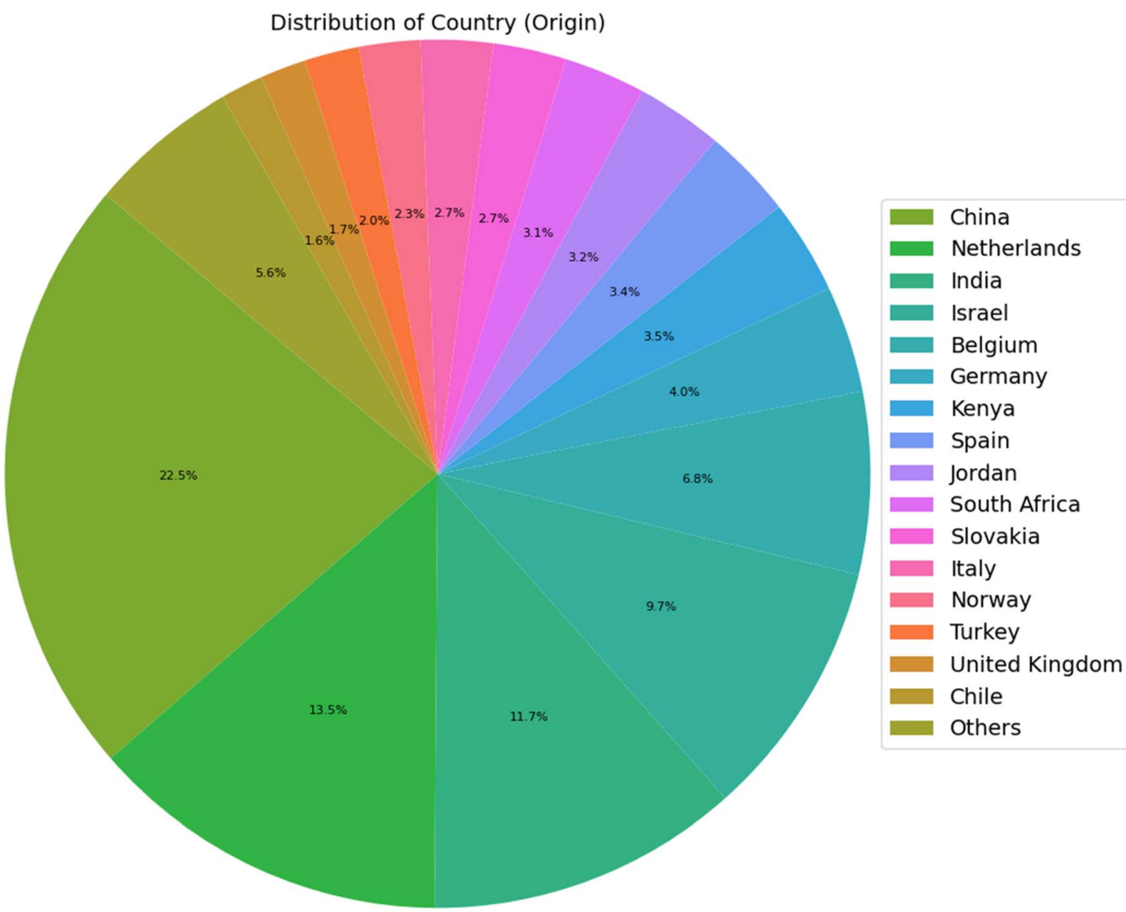

Fig. 8 Distribution of imports among countries.

farming and sensor-based systems are two examples of smart farming technologies that can be combined with nano-fertilizers. Farmers can make fast, accurate, and well-informed decisions regarding nutrient application by incorporating data from multiple sources, including weather forecasts, plant health, soil sensors, and real-time data.[59] Artificial intelligence and machine learning are examples of cutting-edge technologies that can assist with data analysis and interpretation, giving tailored advice for maximizing the usage of nano fertilizers.[60] By optimizing nutrient formulations and release patterns, crop-specific nano-fertilizers can enhance nutrient uptake, yield, and quality, leading to more efficient and sustainable crop production.

9. Challenges and opportunities for nano-fertilizers in Ethiopia

To improve agricultural yield and soil fertility, synthetic fertilizer is essential. However, frequent and excessive use of conventional fertilizers has drawbacks. It can lead to the buildup of pollutants in the soil, detrimental to the ecosystem, causing problems like air pollution, soil acidity, degradation, and water eutrophication. Phosphate fertilizers, often made from apatite, can contain heavy metals like arsenic, cadmium, chromium, copper, zinc, and palladium. These heavy metals pose health risks to humans and animals and negatively impact plant growth. For instance, cadmium is known to be highly toxic and can cause cancer.[61–67]

Another significant challenge is the high cost of imported chemical fertilizers in Ethiopia (see Fig. 7–9). The country uses a lower amount of chemical fertilizer per hectare compared to other nations. In 2022, Ethiopia applied 36.2 kg of chemical fertilizer per hectare on average, significantly less than the global average of about 140 kg per hectare. The reliance on imports and the associated costs pose economic challenges for Ethiopian agriculture.[68]

These challenges highlight the need for alternative fertilizer solutions, such as nano-fertilizers. Nano-fertilizers offer a potentially eco-friendlier and cost-effective approach to increasing crop productivity while minimizing the negative impacts associated with conventional fertilizers.

A recent study conducted in Ethiopia[69] investigated the effects of various nano-fertilizers on teff grain yield and yield components. The field experiment included treatments with nano-nitrogen (nano-N), nano-phosphorus (nano-P), nano-potassium (nano-K), and a combination of nano-NPK fertilizers, comparing them to a control (no fertilizer) and a recommended dose of conventional NPK fertilizer.

The results demonstrated the positive impact of nano-fertilizers on teff growth and yield. Specifically, significant improvements were observed in yield components such as

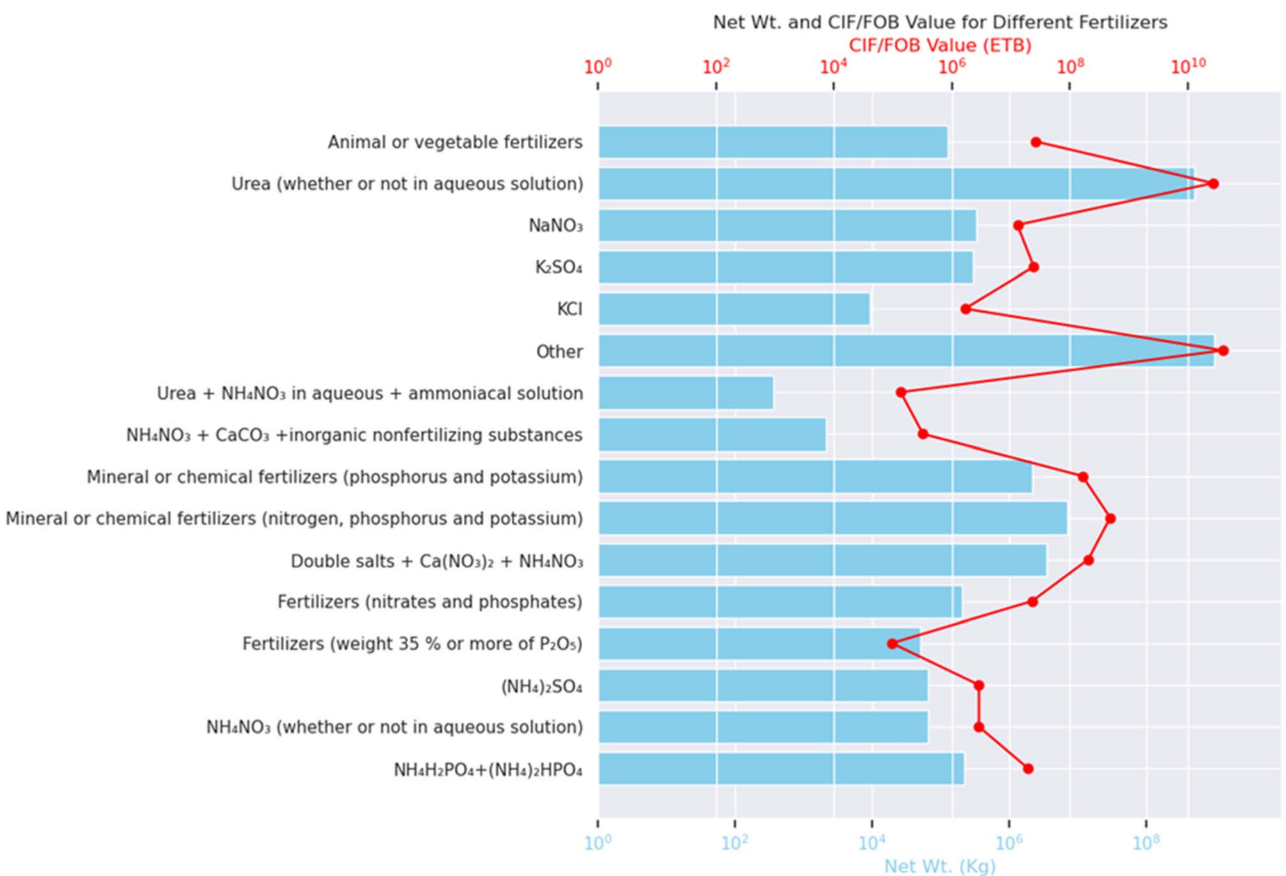

Fig. 9 2022's breakdown of net weight and CIF/FOB value across various fertilizers.

panicle length, panicle weight, and the number of fertile tillers per plant compared to both the control and conventional fertilizer treatments. The application of nano-N and nano-P fertilizers led to particularly noteworthy increases in grain yield.

Importantly, the study highlighted the enhanced nutrient use efficiency achieved with nano-fertilizers, suggesting that plants were better able to absorb and utilize these nutrients compared to conventional fertilizers. This has important implications for both environmental sustainability and economic viability. An economic analysis conducted as part of the study indicated that using nano-fertilizers could potentially lead to increased profitability for teff farmers due to improved yields and reduced fertilizer input costs. These findings underscore the potential of nano-fertilizers to enhance agricultural productivity and contribute to food security in Ethiopia.

While this study provides promising initial evidence, it is crucial to recognize that research on nano-fertilizers in Ethiopia is still limited. Further investigations are needed to assess their long-term impacts on soil health, environmental safety, and human health. Additionally, studies involving diverse crop types and various agro-ecological zones across Ethiopia are essential to develop a comprehensive understanding of the potential and limitations of nano-fertilizers in the country.

Notably, the Bio and Emerging Technology Institute (BETin) is collaborating with the Wondo-Genet Agricultural Research Institute and Addis Ababa University on a project to develop nano-fertilizers from agricultural and industrial waste. This project aims to create sustainable fertilizers using green techniques and has received funding to support its initiatives. Field trials are planned to assess the effectiveness of these nano-fertilizer prototypes on crop yields, nutrient use efficiency, and soil health.

While the potential of nano-fertilizers is evident, research specific to the Ethiopian context remains in its early stages. Further studies are crucial for evidence-based decision-making and to ensure the responsible and sustainable application of nano-fertilizers in Ethiopian agriculture.

10. Conclusion

In essence, by increasing crop output and nutrient use efficiency, nano-fertilizers have the potential to completely transform agriculture. Although nano-fertilizers have great potential for sustainable agriculture, it's crucial to remember that they are still in the early phases of commercialization and widespread acceptance. To completely comprehend their possible advantages and hazards, more research is required to fill in the knowledge gaps. To guarantee their safe and responsible usage, careful assessment of their implications for the environment, health, and society is required. To evaluate their efficacy across various crops, soils, and agro-climatic conditions, as well as to guarantee their safety and environmental sustainability, ongoing research, ongoing scientific exploration, field trials, monitoring activities, regulation, and stakeholder involvement are crucial. Further research and development in this field is necessary to support evidence-based decision-making, monitor their progress, address emerging challenges, maximize the benefits mitigate the potential risks associated with nano-fertilizers, and foster the safe and sustainable use of nano-fertilizers in agriculture.

Data availability

Data will be available by request.

Conflicts of interest

There are no conflicts to declare.

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References

1 T. Stellmacher and G. Kelboro, Family Farms, Agricultural Productivity, and the food (in) security.pdf, *Sustainability*, 2019, **11**(18), 4981, DOI: 10.3390/su11184981.
2 A. Tenaye, Technical efficiency of smallholder agriculture in developing countries: The case of Ethiopia, *Economies*, 2020, **8**(2), 1–27, DOI: 10.3390/ECONOMIES8020034.
3 T. Ayele, D. Goshme and H. Tamiru, Determinants of cereal crops commercialization among smallholder farmers in Guji Zone, Ethiopia, *Cogent Food Agric.*, 2021, **7**(1), 1948249, DOI: 10.1080/23311932.2021.1948249.
4 T. G. Abebe, *et al.*, Growing Use and Impacts of Chemical Fertilizers and Assessing Alternative Organic Fertilizer Sources in Ethiopia, *Appl. Environ. Soil Sci.*, 2022, **2022**, 4738416, DOI: 10.1155/2022/4738416.
5 E. Elka and F. Laekemariam, Effects of Organic Nutrient Sources and NPS Fertilizer on the Agronomic and Economic Performance of Haricot Bean (Phaseolus vulgaris L.) in Southern Ethiopia, *Appl. Environ. Soil Sci.*, 2020, 853552, DOI: 10.1155/2020/8853552.
6 S. Rashid, N. Tefera, N. Minot and G. Ayele, *Fertilizer in Ethiopia: An Assessment of Policies, Value Chain, and Profitability*, International Food Policy Research Institute (IFPRI) Discussion Paper Series, 2014, p. 01304, DOI: 10.2139/ssrn.2373214.
7 A. Eger, *et al.*, Long-Term Effects of Fertilizer Application and Irrigation on Soils Under Pasture Land Use, *J. Soil Sci. Plant Nutr.*, 2022, 801–818, DOI: 10.1007/s42729-022-01084-4.
8 R. Raliya, V. Saharan, C. Dimkpa and P. Biswas, Nanofertilizer for Precision and Sustainable Agriculture: Current State and Future Perspectives, *J. Agric. Food Chem.*, 2018, **66**(26), 6487–6503, DOI: 10.1021/acs.jafc.7b02178.

9 C. An, *et al.*, Nanomaterials and nanotechnology for the delivery of agrochemicals: strategies towards sustainable agriculture, *J. Nanobiotechnol.*, 2022, **20**(1), 11, DOI: 10.1186/s12951-021-01214-7.
10 G. Fellet, L. Pilotto, L. Marchiol and E. Braidot, Tools for Nano-Enabled Agriculture: Fertilizers Based on Calcium Phosphate, Silicon, and Chitosan Nanostructures, *Agronomy*, 2021, **11**(6), 1239, DOI: 10.3390/agronomy11061239.
11 D. Mulla and R. Khosla, Historical evolution and recent advances in precision farming, in *Soil Specific Farming: Precision Agriculture*, ed. R. Lal and B. A. Stewart, Advances in Soil Science, Taylor and Francis, Boca Raton, FL, USA, 2015, pp. 1–35.
12 F. J. Carmona, A. Guagliardi and N. Masciocchi, Nanosized Calcium Phosphates as Novel Macronutrient Nano-Fertilizers, *Nanomaterials*, 2022, **12**(15), 2709, DOI: 10.3390/nano12152709.
13 A. Humbal and B. Pathak, Application of Nanotechnology in Plant Growth and Diseases Management: Tool for Sustainable Agriculture, in *Agricultural and Environmental Nanotechnology*, ed. F. Fernandez-Luqueno, J. K. Patra, Interdisciplinary Biotechnological Advances, Springer, Singapore, 2023, pp. 145–168, DOI: 10.1007/978-981-19-5454-2_6.
14 V. Sharma, B. Javed, H. Byrne, J. Curtin and F. Tian, Zeolites as Carriers of Nano-Fertilizers: From Structures and Principles to Prospects and Challenges, *Appl. Nano*, 2022, **3**(3), 163–186, DOI: 10.3390/applnano3030013.
15 K. Cota-Ruiz, *et al.*, Copper nanowires as nanofertilizers for alfalfa plants: Understanding nano-bio systems interactions from microbial genomics, plant molecular responses and spectroscopic studies, *Sci. Total Environ.*, 2020, **742**, 140572, DOI: 10.1016/j.scitotenv.2020.140572.
16 E. Yusefi-Tanha, S. Fallah, A. Rostamnejadi and L. R. Pokhrel, Zinc oxide nanoparticles (ZnONPs) as a novel nanofertilizer: Influence on seed yield and antioxidant defense system in soil grown soybean (Glycine max cv. Kowsar), *Sci. Total Environ.*, 2020, **738**, 140240, DOI: 10.1016/j.scitotenv.2020.140240.
17 P. Sheoran, S. Goel, R. Boora, S. Kumari, S. Yashveer and S. Grewal, Biogenic synthesis of potassium nanoparticles and their evaluation as a growth promoter in wheat, *Plant Genes*, 2021, **27**, 100310, DOI: 10.1016/j.plgene.2021.100310.
18 W. Legese, A. M. Taddesse, K. Kibret and L. Wogi, Assessing the influence of natural zeolite on toxic heavy metals immobilization and their transfer into Zea mays L., *Bull. Chem. Soc. Ethiop.*, 2023, **37**(6), 1351–1368, DOI: 10.4314/bcse.v37i6.5.
19 M. Li, *et al.*, Molybdenum Nanofertilizer Boosts Biological Nitrogen Fixation and Yield of Soybean through Delaying Nodule Senescence and Nutrition Enhancement, *ACS Nano*, 2023, **17**(15), 14761–14774, DOI: 10.1021/acsnano.3c02783.
20 Y. Zhu, P. Prommana, N. S. Hosmane, P. Coghi, C. Uthaipibull and Y. Zhang, Functionalized Boron Nanoparticles as Potential Promising Antimalarial Agents, *ACS Omega*, 2022, **7**(7), 5864–5869, DOI: 10.1021/acsomega.1c05888.
21 R. A. Dop, D. R. Neill and T. Hasell, Sulfur-Polymer Nanoparticles: Preparation and Antibacterial Activity, *ACS Appl. Mater. Interfaces*, 2023, **15**(17), 20822–20832, DOI: 10.1021/acsami.3c03826.
22 S. Fakharzadeh, *et al.*, Using Nanochelating Technology for Biofortification and Yield Increase in Rice, *Sci. Rep.*, 2020, **10**(1), 1–9, DOI: 10.1038/s41598-020-60189-x.
23 D. Y. Kim, A. Kadam, S. Shinde, R. G. Saratale, J. Patra and G. Ghodake, Recent developments in nanotechnology transforming the agricultural sector: a transition replete with opportunities, *J. Sci. Food Agric.*, 2018, **98**(3), 849–864, DOI: 10.1002/jsfa.8749.
24 S. Ilmudeen, F. Farween, S. Mahaletchumi and D. K. D. I. Kanchana, Advances of Nanofertilizers in Modern Agriculture; A review, *J. Res. Technol. Eng.*, 2022, **3**(2), 19–29.
25 A. Nongbet, *et al.*, Nanofertilizers: A Smart and Sustainable Attribute to Modern Agriculture, *Plants*, 2022, **11**(19), 2587, DOI: 10.3390/plants11192587.
26 A. Yadav, K. Yadav and K. A. Abd-Elsalam, Nanofertilizers: Types, Delivery and Advantages in Agricultural Sustainability, *Agrochemicals*, 2023, **2**(2), 296–336, DOI: 10.3390/agrochemicals2020019.
27 R. Saraiva, Q. Ferreira and G. C. Rodrigues, Phosphorous Nanofertilizers for Precise Application in Rice Cultivation as an Adaptation to Climate Change, *Climate*, 2022, 1–13.
28 N. H. Cao-Luu, Q. T. Pham, Z. H. Yao, F. M. Wang and C. S. Chern, Synthesis and characterization of poly(N-isopropylacrylamide-co-N,N′-methylenebisacrylamide-co-acrylamide) core – Silica shell nanoparticles by using reactive surfactant polyoxyethylene alkylphenyl ether ammonium sulfate, *Eur. Polym. J.*, 2019, **120**, 109263, DOI: 10.1016/j.eurpolymj.2019.109263.
29 M. M. Mikhailov, S. A. Yuryev, V. V. Neshchimenko and A. N. Sokolovskiy, Optical properties and photostability of silicon dioxide powders modified with SiO2 hollow particles and nanoparticles of various oxides, *Radiat. Phys. Chem.*, 2020, **170**, 108661, DOI: 10.1016/j.radphyschem.2019.108661.
30 M. N. A. Hasaneen, M. I. Abou-Dobara, S. M. Nabih and M. M. A. Mousa, Preparation, Optimization, Characterization and Antimicrobial Activity of Chitosan and Calcium Nanoparticles Loaded With Streptomyces Rimosus Extracted Compounds As Drug Delivery Systems, *J. Microbiol., Biotechnol. Food Sci.*, 2022, **11**(6), 1–8, DOI: 10.55251/jmbfs.5020.
31 S. E. Hassan, *et al.*, Rhizopus oryzae-Mediated Green Synthesis of Magnesium Oxide Nanoparticles (MgO-NPs): A Promising Tool for Effluent Treatment, *J. Fungi*, 2021, **8**(5), 1–25.
32 M. Z. H. Khan, M. R. Islam, N. Nahar, M. R. Al-Mamun, M. A. S. Khan and M. A. Matin, Synthesis and characterization of nanozeolite based composite fertilizer for sustainable release and use efficiency of nutrients,

Heliyon, 2021, **7**(1), e06091, DOI: 10.1016/j.heliyon.2021.e06091.
33 K. Tara Meghana and G. Vamsi, Acta Scientific AGRICULTURE (ISSN: 2581-365X), *Nanofertilizers in Agriculture*, 2021, vol. 5, 3, pp. 35–46.
34 R. Borges, S. F. Brunatto, A. A. Leitão, G. S. G. De Carvalho and F. Wypych, Solid-state mechanochemical activation of clay minerals and soluble phosphate mixtures to obtain slow-release fertilizers, *Clay Miner.*, 2015, **50**(2), 153–162, DOI: 10.1180/claymin.2015.050.2.01.
35 N. Baig, I. Kammakakam, W. Falath and I. Kammakakam, Nanomaterials: A review of synthesis methods, properties, recent progress, and challenges, *Mater. Adv.*, 2021, **2**(6), 1821–1871, DOI: 10.1039/d0ma00807a.
36 A. Escudero, *et al.*, Molecular bottom-up approaches for the synthesis of inorganic and hybrid nanostructures, *Inorganics*, 2021, **9**(7), 58, DOI: 10.3390/inorganics9070058.
37 R. Article, A. P. Ingle, and M. Rai, *Strategic Applications of Nano - Fertilizers for Sustainable Agriculture : Bene Fi Ts and Bottlenecks*, 2022, pp. 2123–2140.
38 R. Yaseen, A. I. S. Ahmed, A. M. Omer, M. K. M. Agha and T. M. Emam, Nano-fertilizers: Bio-fabrication, application and biosafety, *Novel Res. Microbiol. J.*, 2020, **4**(4), 884–900, DOI: 10.21608/nrmj.2020.107540.
39 F. Zul, M. Navarro, M. Ashraf and N. A. Akram, Nanofertilizer use for sustainable agriculture : Advantages and limitations, *Plant Sci.*, 2019, **289**, 110270, DOI: 10.1016/j.plantsci.2019.110270.
40 A. K. Bhardwaj, G. Arya, R. Kumar, L. Hamed, H. P. Anosheh and P. Jasrotia, Switching to nanonutrients for sustaining agroecosystems and environment : the challenges and benefits in moving up from ionic to particle feeding, *J. Nanobiotechnol.*, 2022, **9**, 1–28, DOI: 10.1186/s12951-021-01177-9.
41 D. Garg, K. Sridhar, B. Stephen Inbaraj, P. Chawla, M. Tripathi and M. Sharma, Nano-Biofertilizer Formulations for Agriculture: A Systematic Review on Recent Advances and Prospective Applications, *Bioengineering*, 2023, **10**(9), 1–33, DOI: 10.3390/bioengineering10091010.
42 X. Yu and B. Li, Release mechanism of a novel slow-release nitrogen fertilizer, *Particuology*, 2019, **45**, 124–130, DOI: 10.1016/j.partic.2018.09.005.
43 M. Kalwani, H. Chakdar, A. Srivastava, S. Pabbi and P. Shukla, Chemosphere Effects of nanofertilizers on soil and plant-associated microbial communities : Emerging trends and perspectives, *Chemosphere*, 2022, **287**(P2), 132107, DOI: 10.1016/j.chemosphere.2021.132107.
44 R. Belal and A. Gad, Zinc oxide nanoparticles induce oxidative stress, genotoxicity, and apoptosis in the hemocytes of Bombyx mori larvae, *Sci. Rep.*, 2023, **13**(1), 1–9, DOI: 10.1038/s41598-023-30444-y.
45 M. M. Rashid, P. F. Tavčer and B. Tomšič, Influence of titanium dioxide nanoparticles on human health and the environment, *Nanomaterials*, 2021, **11**(9), 2354, DOI: 10.3390/nano11092354.
46 R. Al-mamun, R. Hasan and S. Ahommed, Environmental Technology & Innovation Nanofertilizers towards sustainable agriculture and environment, *Environ. Technol. Innovation*, 2021, **23**, 101658, DOI: 10.1016/j.eti.2021.101658.
47 Razauddin, *et al.*, Effects and Consequences of Nano Fertilizer Application on Plant Growth and Developments: A Review, *Int. J. Environ. Clim. Change*, 2023, **13**(10), 2288–2298, DOI: 10.9734/ijecc/2023/v13i102893.
48 M. Kah, N. Tufenkji and J. C. White, Nano-enabled strategies to enhance crop nutrition and protection, *Nat. Nanotechnol.*, 2019, **14**(6), 532–540, DOI: 10.1038/s41565-019-0439-5.
49 R. Kumari, *et al.*, Regulation and safety measures for nanotechnology-based agri-products, *Front. Genome Ed.*, 2023, 1–12, DOI: 10.3389/fgeed.2023.1200987.
50 L. M. S. Simões, C. Setter, N. G. Sousa, C. R. Cardoso and T. J. P. de Oliveira, Biomass to biofuel densification of coconut fibers: kinetic triplet and thermodynamic evaluation, *Biomass Convers. Biorefin.*, 2022, 631–648, DOI: 10.1007/s13399-022-02393-5.
51 P. Ramalingappa, S. Kumar, S. Prasad and R. Singh, Nanostructured Urea Fertilizer (Nano Urea): A Promising Approach to Sustainable Agriculture, *Food Sci. Reports*, 2023, **4**(5), 84–91, https://creativecommons.org/lice nses/by/4.0/.
52 T. Guha, G. Gopal, R. Kundu and A. Mukherjee, Nanocomposites for Delivering Agrochemicals: A Comprehensive Review, *J. Agric. Food Chem.*, 2020, **68**(12), 3691–3702, DOI: 10.1021/acs.jafc.9b06982.
53 T. K. Sajyan, S. M. Alturki and Y. N. Sassine, Nano-fertilizers and their impact on vegetables: Contribution of Nano-chelate Super Plus ZFM and Lithovit®-standard to improve salt-tolerance of pepper, *Ann. Agric. Sci.*, 2020, **65**(2), 200–208, DOI: 10.1016/j.aoas.2020.11.001.
54 T. Derbe, S. Temesgen and M. Bitew, A Short Review on Synthesis, Characterization, and Applications of Zeolites, *Adv. Mater. Sci. Eng.*, 2021, **2021**, 6637898, DOI: 10.1155/2021/6637898.
55 Y. Sun, *et al.*, Engineered Nanomaterials for Improving the Nutritional Quality of Agricultural Products: A Review, *Nanomaterials*, 2022, **12**(23), 4219, DOI: 10.3390/nano12234219.
56 Z. Zahra, Z. Habib, H. Hyun, H. Muhammad and A. Shahzad, Overview on Recent Developments in the Design , Application , and Impacts of Nanofertilizers, *Agriculture*, 2022, 1–19.
57 N. M. Elekhtyar and A. A. AL-Huqail, Effect of Foliar Application of Phosphorus, Zinc, and Silicon Nanoparticles along with Mineral NPK Fertilization on Yield and Chemical Compositions of Rice (Oryza sativa L.), *Agriculture*, 2023, **13**(5), 1061, DOI: 10.3390/agriculture13051061.
58 P. Chivenge, S. Sharma, M. A. Bunquin and J. Hellin, Improving Nitrogen Use Efficiency—A Key for Sustainable Rice Production Systems, *Front. Sustain. Food Syst.*, 2021, **5**, 737412, DOI: 10.3389/fsufs.2021.737412.
59 E. M. B. M. Karunathilake, A. T. Le, S. Heo, Y. S. Chung and S. Mansoor, The Path to Smart Farming: Innovations and

Opportunities in Precision Agriculture, *Agric.*, 2023, **13**(8), 1–26, DOI: **10.3390/agriculture13081593**.

60 R. Akhter and S. A. Sofi, Precision agriculture using IoT data analytics and machine learning, *J. King Saud Univ. Comput. Inf. Sci.*, 2022, **34**(8), 5602–5618, DOI: **10.1016/j.jksuci.2021.05.013**.

61 M. F. Jilito and D. Y. Wedajo, Trends and Challenges in Improved Agricultural Inputs Use by Smallholder Farmers in Ethiopia : A Review, *Turkish JAF Sci. Tech.*, 2020, **8**(11), 2286–2292.

62 P. Reduction, AGRICULTURAL DEVELOPMENT AND ECONOMIC Promoting Growth with.

63 D. Emmanuel, E. Owusu-Sekyere, V. Owusu and H. Jordaan, Impact of agricultural extension service on adoption of chemical fertilizer: Implications for rice productivity and development in Ghana, *NJAS Wageningen J. Life Sci.*, 2016, **79**(2016), 41–49, DOI: **10.1016/j.njas.2016.10.002**.

64 E. Thomas and J. Omueti, The effect of phosphate fertilizer on heavy metal in soils and Amaranthus caudatus, *Agric. Biol. J. North Am.*, 2012, **3**(4), 145–149, DOI: **10.5251/abjna.2012.3.4.145.149**.

65 L. Al Attar, M. Al-Oudat, K. Shamali, B. Abdul Ghany and S. Kanakri, Case study: Heavy metals and fluoride contents in the materials of Syrian phosphate industry and in the vicinity of phosphogypsum piles, *Environ. Technol.*, 2012, **33**(2), 143–152, DOI: **10.1080/09593330.2011.552531**.

66 P. N. Mwilola, *et al.*, Lead, zinc and cadmium accumulation, and associated health risks, in maize grown near the kabwe mine in Zambia in response to organic and inorganic soil amendments, *Int. J. Environ. Res. Public Health*, 2020, **17**(23), 1–15, DOI: **10.3390/ijerph17239038**.

67 B. G. Luckett, L. J. Su, J. C. Rood and E. T. H. Fontham, Cadmium exposure and pancreatic cancer in South Louisiana, *J. Environ. Public Health*, 2012, **2012**, 180186, DOI: **10.1155/2012/180186**.

68 B. T. Desta and A. M. Gezahegn, Fertilizer Use Trends for Major Ethiopian Crops by Smallholder Farmers, *Ethiop. J. Crop Sci.*, 2023, **11**(1), **https://www.ajol.info/index.php/ejcs/article/view/267246**.

69 M. Tezera, The Effect of Nano Fertilizer on Teff Yield and Yield Components in Ethiopia, *Int. J. Appl. Agric. Sci.*, 2021, **7**(5), 237–241, DOI: **10.11648/j.ijaas.20210705.14**.

