Nanofertilizers: A Green Window of Opportunity for Food Security in Sub-Saharan Africa

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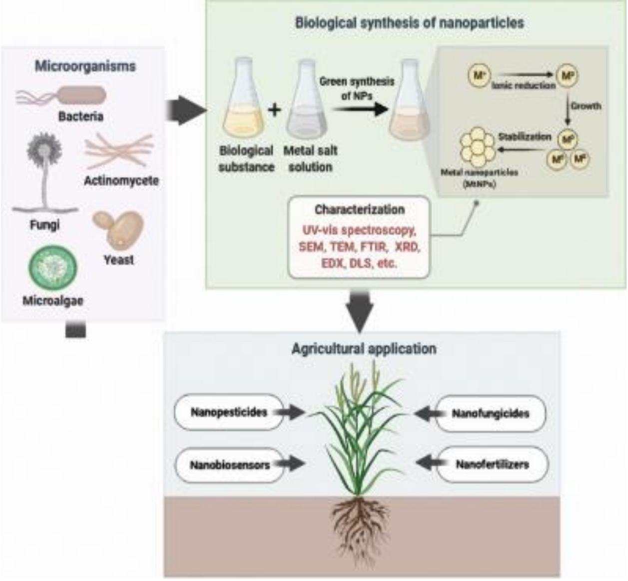
Key Messages

- Nanofertilizers have the potential to increase food security in sub-Saharan Africa (SSA) while reducing the environmental problems of current fertilizers.
- Nanofertilizers have a high Nutrient Uptake Efficiency (NUE) resulting in increased nutritional value of crops as well as small dosage requirements for high yields, 40kg as opposed to 200kg per hectare in conventional fertilizer.
- Nanofertilizers are safe and healthy for producers and consumers, with the right dosage to crop ratio, use of the biological synthesis method and further research into (toxic) effects of general nanoparticle characteristics on crops.
- Lab experiments of nanofertilizers need to be translated into farm practice with small-scale farmers, in order to fill the research gaps needed for its wide adoption. This makes the results tangible for local communities.

Nanofertilizers have advantages over conventional fertilizers in terms of their reduced environmental impacts, cost-effectiveness, and potential higher yields[1, 2, 3, 4]. Nowadays, almost half of the world's population is estimated to be fed with the help of conventional fertilizers[5]. However, SSA is the biggest area without access to this help. These regions have the lowest application rate of fertilizers[6, 7]. One of the consequences of this is *serious* to *alarming levels* of hunger in these regions[8, 9]. With the world's population expected to grow to 9 to 10 billion by 2050[10] food production needs to increase by 70-100% to feed the world[11].

Despite conventional fertilizers fostering food security, these have detrimental environmental impacts, are not efficient in nutrient uptake and not accessible to farmers in SSA. Therefore, the need for a sustainable and efficient alternative fertilizer is vital to foster future food security[12]. One such alternative could be nanofertilizer. These are nutrients, coated or encapsulated with nano-materials. There are a couple of ways of synthesizing nanoparticles. This brief recommends the biological synthesis production method (see fig. 1 and annex 3) in which microorganisms such as bacteria, microalgae, yeast and fungi are combined with minerals to create nanoparticles. This method is cost effective, environmentally friendly, nontoxic and can be made in a simple laboratory environment[13, 14].

Figure 1. Overview of nanofertilizer in biological synthesis method[42]



Benefits of Nanofertilizers for Food Security in sub-Saharan Africa (Annex 1)

Scaling up conventional fertilizer in SSA is not the solution to food insecurity. Currently, the hunger issue in SSA relates both to the unavailability of food but also a lack of nutrition known as 'hidden hunger[15]. The inefficient nutrient uptake (NUE), 20-50%[16, 17], of conventional fertilizers, means it is not a long-term solution for (hidden) hunger. Further, in SSA, conventional fertilizer application is minimal as the cost is 2x the world price due to little to no local production[12]. The high dosage requirement of the current fertilizer also spikes up the price for small-scale farmers[18]. Despite contributing to food security, conventional fertilizers result in detrimental environmental problems. Its industrial production accounts for 1.3% of all global CO2 emissions[19]. Furthermore, the low NUE of conventional fertilizers result in nutrient runoff into the environment, negatively affecting biodiversity and water quality[2].

Thus, a fertilizer must be introduced in SSA that is able to increase availability of food, increase nutritional value of crops, be cost effective and environmentally friendly. The following points show that nanofertilizers have potential to achieve these advantages.

Increased Crop Growth: Nano fertilizers improve adaptability of plants under stress conditions, thus enhancing crop yields[1]. This will increase food availability in SSA, due to drought stress[20].

A Threefold Increase of Nutrient Uptake Efficiency (NUE)[21]: Nanofertilizers can enter crops through foliar or basal application which enhances NUE[2, 22]. This increases the nutritional value of crops (relevant for hidden hunger) and decreases the need for large quantities of fertilizers. While the dosage of conventional fertilizers required to gain a high yield is 200kg per hectare, the dosage needed for nanofertilizers is estimated to be 40kg per hectare[3].

Reduction of Environmental Degradation: Nanofertilizers contribute to reducing soil degradation and water pollution. Due to its enhanced NUE, nanofertilizers allow crops to absorb nutrients more efficiently, which leads to a reduction in runoff of chemical substances in soil and groundwater[2]. Moreover, the ability of slow release of nanofertilizers also leads to the reduction of nitrous oxide and methane – major greenhouse gas emissions[23]. The reduction of environmental degradation is vital to food security in SSA as this will secure a long-term land productivity[24].

Cost Efficiency: The total cost of fertilizers correlates linearly with dosage, so nanofertilizers are cost efficient due to the small dosage requirements. Furthermore, nanofertilizers show a potential to yield higher revenue than conventional ones[3]. This makes nanofertilizers economically accessible to small- scale farmers in SSA. Therefore, the benefits listed above show nanofertilizers provide a green window of opportunity for fostering food security in sub-Saharan Africa.

Challenges of Nanofertilizers for Food Security in sub-Saharan Africa (Annex 2)

Though nanofertilizers have great benefits there are some technological and environmental challenges. At the moment, nanofertilizers are a technology that has not passed the lab experimentation stage[8] which shows there is still a long way to go before it is a viable solution for food security in SSA. Before nanofertilizers can be widely adopted by small-scale farmers and the agroindustry, the following shows a variety of challenges that still need to be addressed or where the science is not definitive yet.

Lacking Research with Small-Scale Farmers in Sub-Saharan Africa: Most research on nanofertilizers does not go beyond lab experiments, greenhouses and experimental fields[8]. However, this research is not taking place in sub-Saharan Africa, where most high-level hunger areas are[9].

Research Gap Regarding the Delivery of Macronutrients: There is contrasting evidence within the scientific community with some seeing the plausibility in macronutrient delivery through nanofertilizers[4, 25] and others a lack of[12]. Macronutrients are an essential factor in helping protect the plant against harmful stressors[26] and overall plant growth[27].Therefore, to increase crop yield which fosters food security in sub-Saharan Africa, macronutrient uptake is essential in fertilization. Thus, more research is needed to make definitive scientific conclusions.

Harmfulness of excessive usage: The excessive use of nanofertilizer alters its efficiency and increases its toxicity therefore becoming harmful for plants and humans[1, 28, 20]. It is necessary that small-scale farmers have the correct knowledge on dosage to crop ratio.

Disseminating knowledge to farmers: It is challenging to disseminate knowledge about nanofertilizers to small-scale farmers in SSA. Without visible evidence of the benefits of nanofertilizers farmers will not be eager to acquire the knowledge to incorporate this new technology[8,30]. Once farmers are interested in the use of nanofertilizers, access to accurate information on application processes must be provided. Precise knowledge is needed because of sensitive reactivity to certain crops and tailored dosage to crop ratios[3, 25, 29].

Contrasting evidence regarding the upscaling of biological synthesis production: Some researchers say this method can easily be scaled up[13, 31.] Others say that the time and cost of processing and culturing microbes or crops is too high for it to be a likely route for upscaling32. It is essential that this is investigated more. If scaling up is not applicable for this method there are minimal benefits for food security in SSA.

Transition Potential of Nanofertilizers

It is important to recognize that the adoption of nanofertilizer technology would require integration into already existing agricultural systems dominated by conventional fertilizers. The potential of nanofertilizers to contribute to crop yields and reduce unsustainable farm practices does not depend solely on its technological features. Unlike conventional fertilizers, there is no large-scale agricultural practice or system in which nanofertilizers are embedded yet. For conventional fertilizers there are large-scale production sites, established trading connections, national and international regulatory frameworks, and agronomic networks that disseminate information to farmers.

Farmers are familiar with the use, effect, and pricing of conventional fertilizers. For nanofertilizers these systemic components need to co-evolve with the technology itself to materialize on a larger scale in agricultural practices. Since SSA has very little fertilizer usage, there is not necessarily a dominant fertilizer system in this region. The fact that the support system surrounding fertilizers is not developed in SSA provides a green window of opportunity. With attention being paid not only to technological innovation but also to the institutional infrastructural and economic needs for nanofertilizer implementation, it can be a realistic alternative to conventional fertilizers.

Furthermore, agricultural practices are based on many other components than merely technological features and potential. In SSA, agricultural practices have been a part of communities for centuries and include their culture, traditions as well as long-term investments in existing agricultural techniques. These influence decisions regarding the adoption of new technologies in agricultural communities.

Lab experimentation biological synthesis nanoparticles in drought stress[40]

Capped and uncapped iron oxide nanoparticles on foxtail millet in drought stress conditions

Findings:

- Without iron oxide nanoparticles foxtail millet shows decline in performance
- With iron oxide millet shows increase in performance under varying dosages
- Iron is an essential micronutrient for plant growth and human health

Conclusion: Green synthesized iron oxide is easily up taken by foxtail millet in drought stress conditions, especially when capped.

Significance for food security: Resistance in drought stress shows potential for crop growth in SSA, and micronutrient uptake combats iron deficiency (a part of hidden hunger) in the population.

Fertilizer Company Nano Urea claims

- New product by fertilizer company, released to market in 2022
- Their claims for sustainability, economic efficiency, and yield increase are questioned by some scientists[12, 44, 45]
- They claim that one bottle (500ml, 20g urea) has the same effect as one bag (45kg, 20kg Urea) of urea fertilizer[44]
- A lot of concerns by interviewed experts about the potential negative impacts on food security of nano urea[12, 45, 46, 47]
- There is a lack of (inter)national regulation to prevent misleading nanofertilizer products from entering the market.

Significance for food security: New nanofertilizer products need to be regulated and approved to make sure companies are not putting profits over food production, and claims over facts.

Conclusion

Thus, for the adoption of nanofertilizers in SSA, it is important not only to focus on technological aspects but include the wider systemic components which need to co-evolve with nanofertilizer technology. Further, it is important to recognize agriculture as a social practice just as much as it is a technological practice. Therefore, it is vital to look wider than a purely scientific and political lens and take this cultural aspect into account.

Policy Recommendations

- **Create international standardization for nanofertilizers regarding its ability to increase yields, environmental impacts, and health implications:** As shown in the case of nano urea, the demand for alternative fertilizers can also be misused. Therefore, the FAO in collaboration with national governments and other organizations as they see fit, should agree on scientific international standards deciding on what nanofertilizers are permitted on the market.
- **Subsidize field trials with small-scale farmers in SSA:** This is necessary to determine the possibilities of macronutrient delivery, toxicity, optimal dosage, cost efficiency and the effectiveness of nanofertilizer synthesis methods in relation to food security in SSA. Moreover, this gives farmers visible evidence of the potential benefits of nanofertilizers.
- **Disseminate information about nanofertilizers to small-scale farmers in SSA using their existing information methods:** It is important to find efficient ways to transfer the knowledge to farmers to foster sustainable food security. Using their existing information methods makes knowledge transfer more easily accessible and implementable. Example: iSDA-Africa (advisor for African agribusinesses) is working on using WhatsApp (which many farmers in SSA already have) in combination with ChatGPT to provide them with specialized information.
- **Research on wider systemic needs for implementation of nanofertilizer:** As stated in the transition potential of nanofertilizer, technologies never solely transition on their own. When looking into nanofertilizer it is essential that these wider systemic connections are taken into consideration during research and policy making.

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Annex

Annex 1. Detailed Benefits of Nanofertilizers

Nanofertilizers serve as a sustainable agricultural tool, enhancing crop yields and demonstrating environmentally friendly traits compared to conventional chemical fertilizers. Additionally, they show cost-efficient potential.

Enhanced Crop Growth

Abiotic and biotic stresses can significantly hinder plant growth. Abiotic stresses include drought, heat, salinity among others while diseases and pests are major biotic stresses to plant growth[22]. It is reported that stresses negatively affect plants' productive capacity, and abiotic stresses account for approximately 70% of yield reductions[1]. Another study found that salinity and drought accounts for 50% of crop yield reductions[33]. However, nanofertilizers improve adaptability of plants under stress conditions, thus enhancing yields[1]. There are a multitude of reports on enhanced crop growth, which includes rice, wheat, maize, and soybean[1].

Nutrient Uptake Efficiency (NUE)

Enhanced nutrient uptake efficiency (NUE) is a key benefit of nanofertilizers, contributing to their environmentally friendly nature. It is reported that nanofertilizers can enhance NUE threefold[21]. Improved NUE results in reduced nutrient losses and a decreased need for larger quantities of fertilizers. Thus, nanofertilizers contribute to reducing environmental degradation such as soil degradation and water pollution. Several characteristics of nanofertilizers will help increase nutrient uptake efficiency. Due to their small size, nanofertilizers have the ability to enter plants and crops by foliar or basal application, which enhances NUE[2, 22]. Furthermore, nanoparticles exhibit a notable ratio of surface area to volume, facilitating both chemical reactivity and physical responses[2, 22]. This can increase nutrient availability and nutrient uptake efficiency for plants and crops[22]. Also, nanofertilizers' slow and controlled release of nutrients will minimize nutrient losses and lead to nutrient availability and enhanced NUE[1, 2]. Lastly, nanofertilizers have high water solubility, leading to enhanced nutrient dispersion in soil, thus increasing nutrient availability for plants and crops[22].

Environmental Impacts

Conventional fertilizers, characterized by their low NUE, are often applied in high dosages. This practice results in a significant portion of applied fertilizers being lost in the soil, leading to multiple consequential environmental impacts. The low NUE of these fertilizers may result in the accumulation of heavy metals and their compounds in the soil, causing soil pollution[34]. Furthermore, nutrient runoff may reach rivers and lakes, where high levels of nitrogen accumulation can cause algal bloom, negatively impacting aquatic ecosystems and human lives[2, 35]. Nutrients leaching into groundwater can also contaminate drinking water[2]. Additionally, there exists a correlation between N2O emissions and the nitrogen application rate, with conventional nitrogen fertilizers contributing to N2O emissions[36]. In contrast, nanofertilizers, owing to their enhanced NUE, can mitigate these negative impacts on the environment. It is also reported that slow release of nanofertilizers can also contribute to the reduction of N2O and CH4 emissions in the rice soil ecosystem[23].

Cost Efficiency

The unit price of nanofertilizers is currently higher than that of conventional ones. However, as the total cost of fertilizers correlates linearly with dosage, the characteristic of nanofertilizers requiring lower dosage contributes to cost efficiency. While the dosage of conventional fertilizers required to gain a high yield (greater than 8.0t per hectare) is 200kg per hectare, the dosage needed for nanofertilizers is estimated to be 40kg per hectare. Furthermore, high efficiency nanofertilizers show a potential to yield higher revenue than conventional ones. Also, co-dosing of conventional and nanofertilizers has the potential to lower the cost and increase yields[3].

Annex 2. Detailed Challenges of Nanofertilizers

Lacking research with farmers in sub-Saharan Africa

Currently nanofertilizer research is still scratching the surface as an interviewed researcher from the International Fertilizer Development Center (IFDC) states. Most research does not go beyond lab experiments, greenhouses and experimental fields. Therefore, future research must extend into long term field trials in collaboration with farmers actually working in the industry. An example of this is what researchers are doing in South America[37]. The field trial in South America investigates nanofertilizers that are based on titanium oxide, zinc oxide and zeolite. In total 1500 farmers will be trained to use nanofertilizers and results should be generated from these trials on the feasibility on different synthesis methods, environmental risks, NUE and biomass production, changes in soil composition and CO2 and N2O emissions mitigations. Therefore, the field trial is quite comprehensive. The training of the farmers as well as creating a spin off business model aim to look into the potential of nanofertilizers as an upscaled product on the fertilizer market. This, however, should additionally have a focus in high level hunger areas[9] in sub-Saharan Africa due to this being the largest region with food insecurity issues[9]. Therefore, to foster food security, the use of nanofertilizers must also be trialed amongst a small number of farmers in SSA, in order to look into its upscaling potential. The project in South America is a good guideline for this.

Research gap regarding macronutrient uptake of nanofertilizers

There is a research gap present in relation to nanofertilizer and its delivery of the most important macronutrients in plants; Potassium, Nitrogen and Phosphorus. Some extra information on macronutrients may aid in helping to understand precisely why this is such an important point to be investigated. Macronutrients can be divided into primary and secondary categories. The primary macronutrients are what are taken up by the plant in large quantities and are essential for their growth and overall good state[37]. The main primary macronutrients are Nitrogen, Phosphorus and Potassium which are also the main nutrients found in current fertilizers[38]. Nitrogen out of these big three nutrients is considered to be most important in making sure the plant is healthy due to protein build up. Phosphorus is vital in strengthening the plants' ability to store energy which also entails its photosynthesis abilities. Potassium helps protect the plant against diseases and abnormal weather conditions, also vital to a plants survival[384].

Harmfulness in excessive usage of nanofertilizer

An interviewed researcher from Connecticut Agricultural Experiment Station states that the excessive use of nanofertilizer alters its efficiency and increases its toxicity therefore becoming harmful for plants and humans. This is further substantiated by several academic articles claiming supra optimal dosages, type of host plant and environmental conditions can all be factors that lead to a change in nanoparticle composition turning it into a more harmful substance[1, 28, 29]. Such toxicity can be reduced but only once the effects of the categories: general characteristics of the nanoparticle (size, morphology, type of coating in some cases, concentration, electrical charge and crystal structure) the type of application and applied experimental method are addressed in a clear overview[43]. Thus, further and more advanced research on toxicological data of nanoparticles including the categories above is needed. Furthermore, international standardization on safe nanofertilizer usage is needed in order to upscale production and application.

Disseminating knowledge to farmers in SSA

There is a lingering question of whether farmers are willing to take up this new technology, looking at the time and energy it takes to acquire such knowledge. According to a researcher from the IFDC and a farmer from Rural Farmers Hub in Nigeria, for the technology to be used amongst small-scale farmers in sub-Saharan Africa it needs to be economically viable, it needs to have visible evidence of success and it needs to contain a well presented and thought-out value chain, so farmers know directly what they are dealing with. Field trials like the ones stated above can provide such visible evidence as well as present a thought-out value chain for farmers to work with.

Annex 3. Biological Synthesis Method of Nanofertilizer Production

Three synthesis methods of nanoparticles

There are several ways to synthesize nanoparticles for nanofertilizers: chemical, physical and biological methods. The most common nanoparticle synthesis method is chemical synthesis, which is also called the bottom-up approach, where nanoparticles are built up from atomic scale by chemical reactions. This method enables better control of the particle size and reduces impurities. Physical synthesis, which is also called the top-down approach, is an approach where bulk materials are milled into nanoscale. While the process has disadvantages such as less size control and more impurities, it is used to produce nanofertilizers due to its ease and less time in synthesis and potential for large-scale production. The current focus of this brief is on a method called the biosynthesis approach where plants, bacteria and fungi are employed. This method has advantages over chemical and physical synthesis approaches as it is cost effective, environmentally friendly, and less toxic[4, 14]. These reductions in toxicity and environmentally friendly effects are due to the use of less chemicals compared to chemical and physical methods of production. This results in less chemical contamination to humans and the environment. Moreover, this method of production is less energy intensive and thus a more environmentally friendly option due to the reduction of equipment needed to reduce bulk material to nanomaterial[39].

Production of biological synthesis nanoparticles

To produce one of the nanoparticles, iron oxide nanoparticles, according to the biological method, Sreelakshmi et al. (2021)[40] explains seaweed is washed, dried, and stored, then which is added to heated water, stirred, filtered, and used as the seaweed bio extract. This extract is then used to synthesize the iron oxide nanoparticles.

Benefits of biological synthesis method

During an interview with a researcher from India, some benefits of biological synthesis methods over other synthesis methods were elaborated on. The method does not use many chemicals, is affordable and easy to make in a simple laboratory environment. Singh et al. (2016)[41] suggests that it is environmentally friendly and cost-effective method, and it can avoid toxic chemicals and high energy demand. It is also stated that this method allows rapid production of fertilizers.

Challenges of biological synthesis method

In terms of the production of nanofertilizers there is some contrasting evidence when it comes to the upscaling of the biological synthesis method. According to chemists specializing in biological synthesis production[13, 31], this method can be easily upscaled as it is a cost-effective method that uses simple reaction processes that are able to be reproduced in simple lab sites worldwide. However, another source[32] shows that the time and cost of processing and culturing microbes or crops in the biological synthesis method is too high for it to be a likely route for upscaling.

Annex 4. Internviews

No.	Institution	Topic	Country	Date
1.	Amrita University	Green Synthesized Iron-Oxide Nanofertilizers	India	20.11.23
2.	Wageningen University & Research	Nanotechnology	Netherlands	23.11.23
3.	International Fertilizer Association (IFA)	Innovative Fertilizer Products and Food Security	Germany	24.11.23
4.	International Fertilizer Development Center	Research on Nanofertilizers	Ghana	28.11.23
5.	Rural Farmers Hub	Small-Scale Farming Practices and Fertilizer Use in Nigeria	Nigeria	29.11.23
6.	Wageningen University & Research	Soil Science and Food Security in Sub-Saharan Africa	Netherlands	29.11.23
7.	Small-Scale Farming Practitioner	Small-Scale Farming Practice	Nigeria	29.11.23
8.	Indian Agricultural Research Institute	Plant Physiology	India	30.11.23
9.	IDFC – Connecticut Agricultural Experiment Station	Development of Nanofertilizers	US	30.11.23
10.	iSDA	Farming Practices and Small-Scale Farming in Sub-Saharan Africa	Several countries in Africa	05.12.23