

Abstract

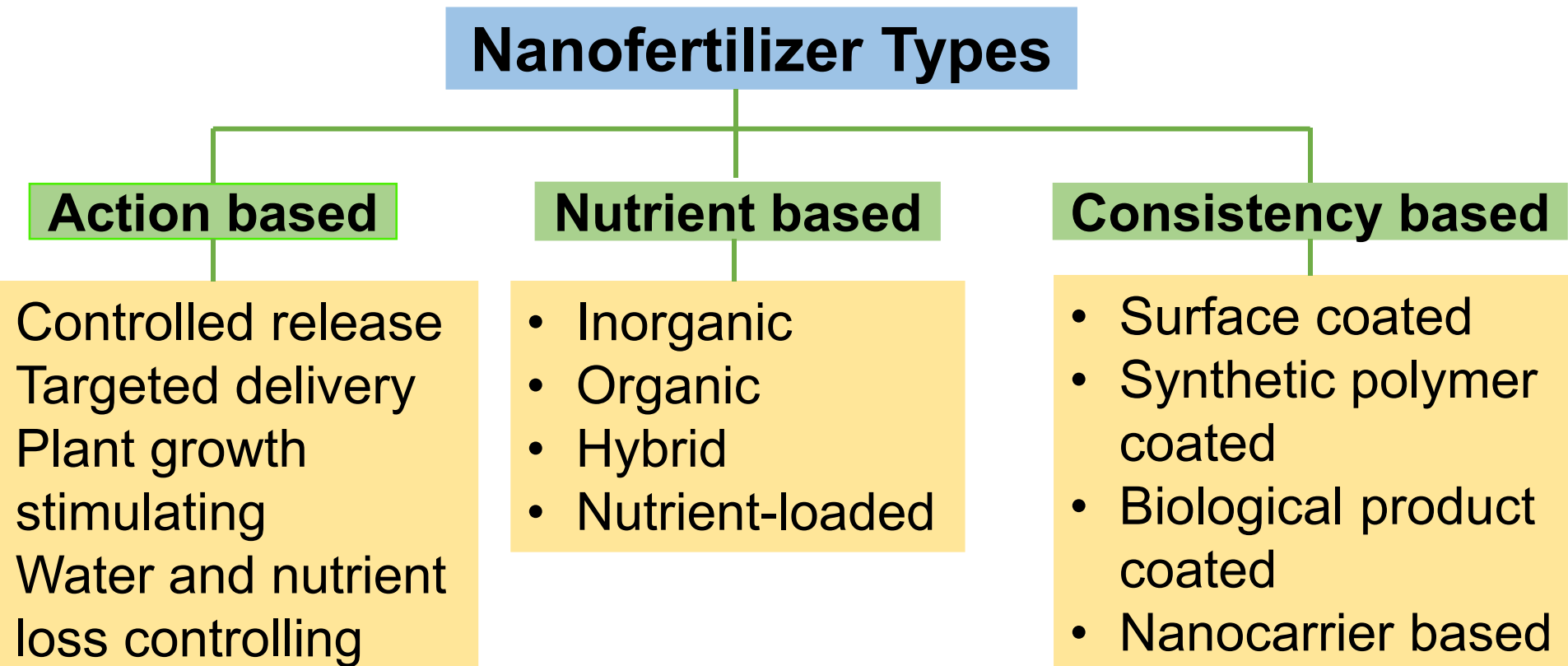
The population of the world is rapidly increasing at a remarkable pace and is predicted to be approximately 9.6 billion by 2050. Feeding the population without expanding natural resources is one of the urgent challenges of the 21st century, which tends to push a highly advanced development in the agricultural sector to minimize the worldwide poverty and hunger, assuring food safety. Conventional fertilizers (CFs) are extensively used as the source of plant nutrition to enhance food production widely. Although having effectivity, CFs lead to environmental risks, including soil degradation, water pollution and greenhouse gas emissions. Some recent statistical reports stated that the applied key macronutrient elements, like 40-50% of nitrogen, 80-90% of phosphorus, and 50-90% of potassium, are lost by the soil because of irregular use of fertilizer without considering nutrient release patterns. Therefore, nanotechnology in agriculture has emerged as a promising alternative to produce environmentally friendly fertilizers with high nutrient-use efficiency. In response, a review analysis was conducted on the latest research on green chemistry-based nanofertilizers (NFs) design and formulation, their application mode, field performance, and environmental impact, mainly highlighting the potential benefits of NFs with current limitations and future challenges in wide-scale application. NFs are engineered at the nanoscale to increase nutrition management and reduce nutrient leaching into groundwater, offering a revolutionary alternative directly supported by the several UN Sustainable Development Goals (SDGs), particularly SDG 2 (zero hunger). Additionally, NFs can be considered nanobiofertilizers when combined with microorganisms that enhance abiotic stress tolerance. However, despite having several benefits, NFs face some challenges, including limited long-term safety analysis, lack of standardized regulations, and high costs. The excessive release of nanomaterials into the environment and the food chain may endanger human health. Future research must focus on cost-effective green production methods, field trials, and extensive risk evaluation to ensure sustainable and safe agricultural applications.

Keywords: Nanofertilizers, Green Chemistry, Nutrient, Environmental Impact, Sustainable Agriculture.

Introduction

NFs are essential to reduce the use of inorganic fertilizers and reduce their adverse effects on the environment, as they are highly reactive, can penetrate the epidermis, and enable slow release and dispersion, thus improving nutrient-usage efficiency.

- ❖ Global agriculture faces challenges of sustainability, food security, and climate adaptation.
- ❖ NFs engineered at the nanoscale and can be formulated as nanoparticles or nano-encapsulated nutrients.
- ❖ Potential benefits include higher crop productivity, reduced environmental pollution and nutrient leaching.
- ❖ Although promising, NFs lack extensive field trials, safety profiling, and long-term environmental risk assessment.
- ❖ This study explores design and formulation, application modes, field performance, environmental impacts, benefits, limitations, and future challenges of NFs.



Design & Formulation of NFs

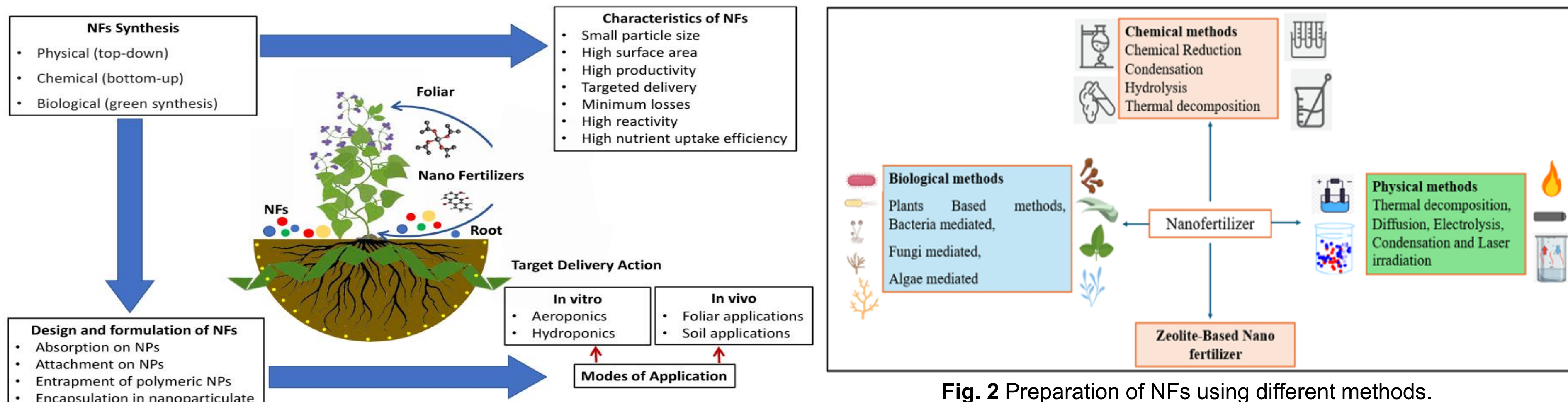


Fig. 1 Overview of design and formulation of NFs.

Application Modes

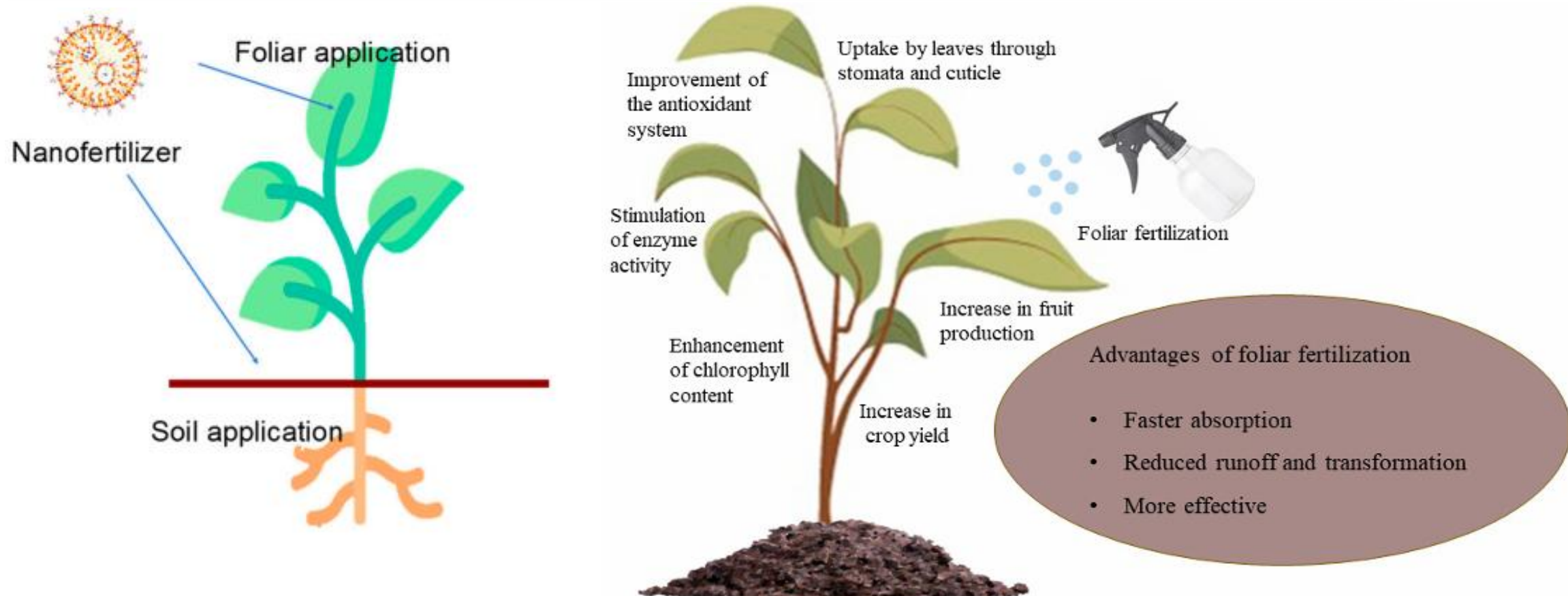


Fig. 3 Different application modes of NFs.

Field Performance & Agronomic Outcomes

Table 1: Application of NFs and their effect on productivity of different crops .

Nano fertilizers	Crop	Yield increment (%)
Nano fertilizer + Urea	Rice	10.2
Nano fertilizer + Urea	Rice	8.5
Nano fertilizer + Urea	wheat	6.5
Nano fertilizer + Urea	wheat	7.3
Nano-encapsulated phosphorous	Maize	10.9
Nano-encapsulated phosphorous	Soybean	16.7
Nano-encapsulated phosphorous	wheat	28.8
Nano-encapsulated phosphorous	Vegetables	12.0–19.7
Nano chitosan-NPK fertilizers	wheat	14.6
Nano chitosan	Tomato	20
Nano chitosan	Cucumber	9.3
Nano chitosan	Capsicum	11.5
Nano chitosan	Beet-root	8.4
Nano chitosan	Pea	20
Nano powder of cotton seed and ammonium fertilizer	Sweet potato	16
Aqueous solution on Nano iron	Cereals	8–17
Nanoparticles of ZnO	Cucumber	6.3
Nanoparticles of ZnO	Peanut	4.8
Nanoparticles of ZnO	Cabbage	9.1
Nanoparticles of ZnO	Cauliflower	8.3
Nanoparticles of ZnO	Chickpea	14.9
Rare earth oxides nanoparticles	Vegetables	7–45
Nano silver + allicin	Cereals	4–8.5
Iron oxide nanoparticles + Calcium carbonate nanoparticles + peat	Cereals	14.8–23.1
Sulfur nanoparticles + silicon dioxide nanoparticles + synthetic fertilizer	Cereals	3.4–45

Table 2: Comparison of fertilization approaches.

Fertilization Approach	Main Results
Nanofertilizers (urea-hydroxyapatite, potassium sulfate), conventional fertilizers	Nanofertilizers at half dosage comparable to conventional fertilizers in yield and nutrient content.
Nano NPK fertilizer	Increased yield and nutrient use efficiency, reduced environmental impact.
Hydroxyapatite nanoparticles for P availability	Improved P availability in alkaline soils.
Biodegradable hydroxyapatite nanoparticles	Enhanced soil health and crop yield.
Biogenic potassium nanoparticles	Promoted wheat growth, enhanced potassium uptake.
Hydroxyapatite nanohybrids with Zn and Mg	Enhanced growth and nitrogen uptake.
Urea-hydroxyapatite nanohybrids	Improved nutrient uptake, slow nitrogen release.
NPK nanofertilizer mixtures	Improved nutrient use efficiency and yield.
Potassium sulfate nanoparticles	Improved nutrient availability and uptake.
Nanopotassium sulfate	Improved grape yield and quality, enhanced potassium efficiency.

Environmental Fate and Impact

Nanofertilizers	Size and shape	Remarks
Nano zeolite-based nitrogenous fertilizer	66 nm for NO ₃ ⁻ and 77 nm for NH ₄ ⁺	Compared to conventional fertilizer, soil fertilized with nano-fertilizer showed reduced N ₂ O emission and a lower CH ₄ flux.
Apatite NF	Spherical shape with diameters of 15.8 & 67.4 nm	Production of biomass was increased by 18.2% above ground and 41.2% below ground. As a novel class of P fertilizer, apatite nanoparticles may improve agronomical yield while lowering the danger of water eutrophication.
Nanoclay polymer composite loaded with urea	Hexagonal shaped nano-scale bentonite particles	In the leaching study the decrease of NO ₃ ⁻ -N was 71.6, 78.5 and 68.8% by DCD, Schiff base and neem oil based NCPC, respectively, at the depth of upper 5 cm in the soil column compared to urea.
Acrylic Acid + Acryl amide nanoclay polymer composite (NCPC)	Hexagonal shaped nano-scale bentonite particles	NCPC reduced N ₂ O emission by 16.1% in rice and 12.4% in wheat as compared to urea.

Benefits Vs. Limitation

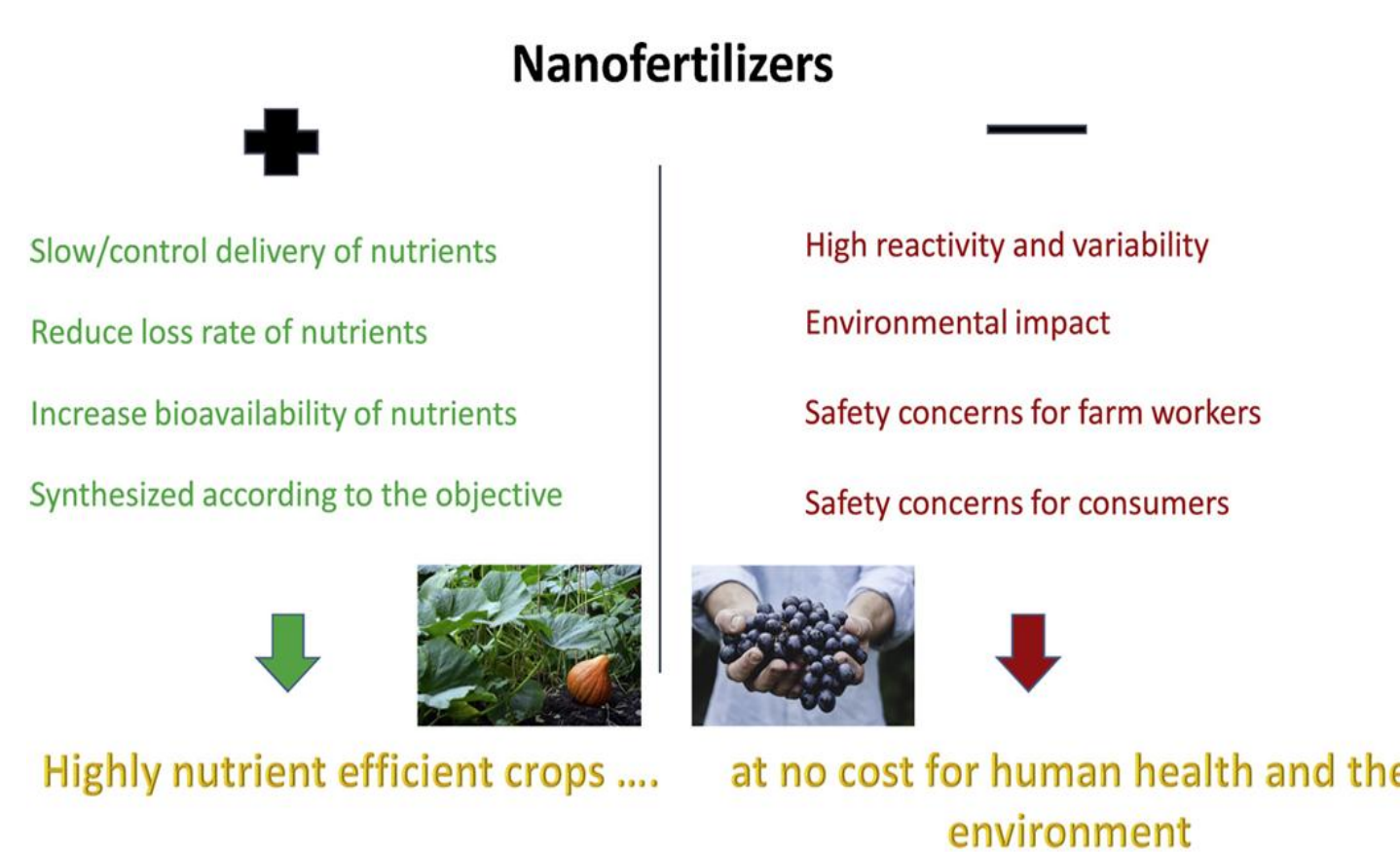
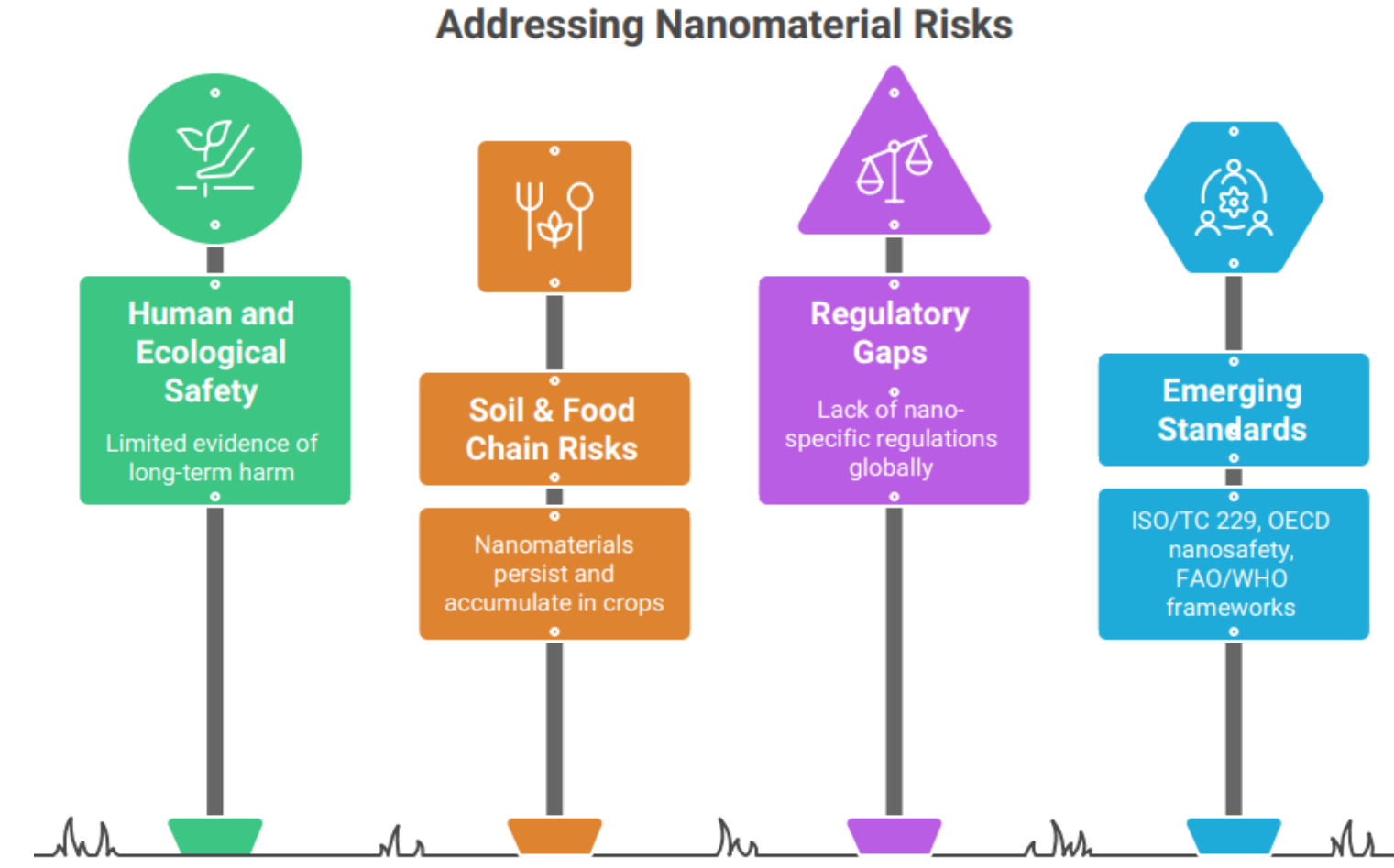


Fig. 4 Advantages and limitations of NFs.

Safety, Regulation and Standard



Future Challenges and Research Perspective

Future Challenges for NFs

- ❑ Nutrient release mechanisms.
- ❑ Targeted delivery systems.
- ❑ Biological interactions with soil microorganisms.
- ❑ Cost-effective and sustainable synthesis.
- ❑ Evaluation of food chain transfer risks..
- ❑ Customized formulation and waste reduction.

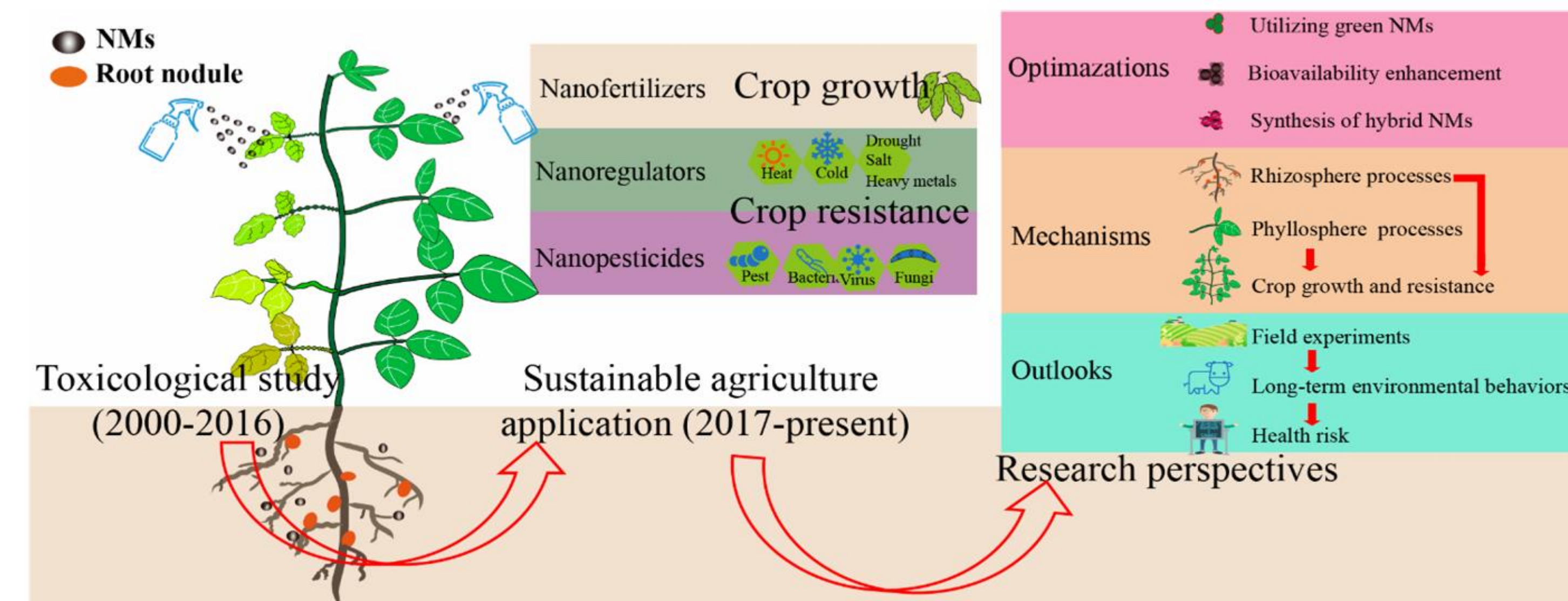


Fig. 5 The nano-agricultural development and perspectives.

Methodology

This study was conducted using databases of relevant peer-reviewed articles (Scopus, Web of Science, PubMed) covering 2015-2025.

Conclusions

- NFs are emerging as a promising strategy to enhance nutrient use efficiency and crop productivity.
- NFs support SDGs by improving crop productivity.
- Research is mostly limited to lab and greenhouse studies; field trials remain scarce.
- Long-term effects on soil, water, and food chain transfer are still underexplored.
- Future progress requires green synthesis, harmonized safety standards, and farmer training.
- Balancing innovation with biosafety will be key for sustainable NF adoption.

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