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News & Views

A glimpse into a new era of nanozyme-driven whole-agrofood safety

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Global climate changes, such as extreme weather, sea levels rise, and biodiversity decline, have destructive impacts on the global agrofood system, in terms of crop yield, agrofood quality and consumer safety. Those stressed conditions and environmental pollution for crop and agrofood prompt us to take immediate action to develop a whole-new-era agrofood system from the perspective of sustainability [1]. Nanozymes, nanomaterials with enzyme-mimicking properties that possess low cost, facile preparation, tailorable activity, and greater robustness against stringent conditions than their biocountparts, have emerged as the times require [2]. Benefiting from their highly tailorable and stable enzyme-mimicking functionalities, nanozymes can survive and thrive in the global agrofood sector under destructive conditions by enhancing crop stress resilience and agrofood quality control.

Consequently, our study shed a light on the whole-new-era agrofood safety driven by nanozymes, including agrofood yields and quality safety, highlighted distinctive superiorities of nanozyme-enabled agrotechnologies, and specified their advantageous directions, providing a comprehensive overview of nanozyme-safeguarded agrofood safety (Fig. 1).

Enhancing crop stress resilience. Global climate change has intensified biotic and abiotic stresses on crop, such as virus, salt, drought, cold, heat, and light stresses, thus increasing the burden on global agrofood yields. The traditional methods to improve crop stress resilience include (1) genetic engineering, (2) cultivation management, (3) rational use of various fertilizers, (4) appropriate application of plant growth regulators. Nevertheless, those strategies suffer from challenges, such as time consumption, trial-and-error, high professionalism, and damage to environment. This necessitates exploiting reformative, effective, and sustainable agrotechnologies to eliminate stressed conditions on crops by reducing time exploration and harm to the environment, as well as improving programmability and maneuverability in agricultural practices.

Fundamentally, reactive oxygen species (ROS) are active agents for damaging of important crop biomolecules, such as proteins and nucleic acids, under stress conditions [3]. To avoid this damage, ROS-modulating enzymatic systems in crops, consisting of oxidase, peroxidase, catalase, superoxide dismutase, reductase, etc., often play a vitally important role in balancing exogenous and endogenous ROS stresses through specific catalytic pathways (Table S1 online). From this perspective, nanozymes with ROS-modulating activity show great potential in the improvement of crop stress resilience compared with aforementioned intervention approaches because nanozymes can reproducibly and directly regulate ROS levels in crops. In this regard, nanozymes with antioxidant enzyme-mimicking activity can either mitigate crop stress by the ROS-scavenging pathway or improve the crop stress tolerance by creating a suitable ROS environment below the threshold value in crop to stimulate defensive pathways of stress.

Nanozymes with antioxidase-mimicking activities can scavenge undesirable ROS levels in cellular metabolic processes under stress conditions. Nanoceria with ROS-scavenging activities as nanozymes could augment the growth of crops under heat, light, and dark chilling stress by subsiding the excessive ROS in leaves, reflected in Rubisco carboxylation rates, carbon assimilation rates, and quantum yield of photosystem II. In the ROS-scavenging process, nanozymes exhibited a distinctive superiority over known crop natural enzyme scavengers: nanozymes could effectively eliminate hydroxyl radicals that unable to be scavenged by the founded natural enzyme scavengers in crop. In addition, the unique physical characteristics of nanoceria, such as small size, sphere, and negative charge, have also reinforced with their transportation inside chloroplasts [4]. Moreover, nanozymes containing crop-required elements have also played an important role as nanofertilizers in addition to ROS-scavengers. γ-Fe_2O_3 nanozymes with sizes of 4–15 nm as nanofertilizers could boost the crop growth by increasing carbon assimilation, activating the antioxidative system, and regulating plant hormones in nodules, which potentially elevated 55.4% and 99.0% of the crop biomass in the shoots and nodules, respectively, as well as 13.2% of the nitrogen fixation efficiency compared with commercial iron fertilizer [5]. Moreover, nanozymes with ROS-generating activities could be developed as stressed vaccines for crops under normal conditions. Silver nanoparticles (NPs) with ROS generation activity could enhance crop resilience against salinity stress by the seed priming method to stimulate the defense pathways of crops and form "stress memory", which could increase the fresh and dry weights of crops by 58% and 34% under salt stress, respectively [6]. More-

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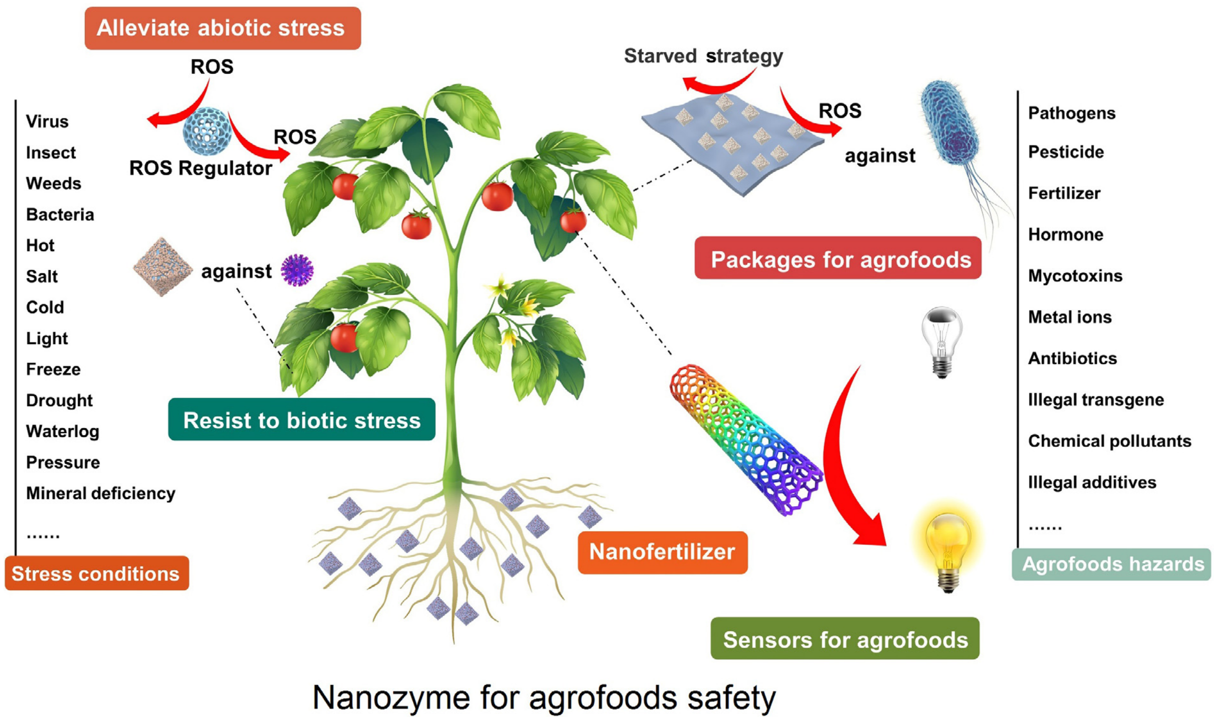

Fig. 1. Illustration of the whole-new-era agrofood safety safeguarded by nanozymes.

over, nanozymes with protease-like activity could address the biotic stress caused by viral diseases in crop. Chiral 3 nm $Cu_{1.96}S$ NPs with protease-like activity can site-selectively hydrolyze the amide bond between Asn 101 and Pro 102 to cleave the capsid of tobacco mosaic virus under sunlight, which is reflected in an excellent inhibition efficiency of 98.7% in protoplasts and 92.6% in crops while avoiding hypersensitive response and immense environmental impact [7].

Improving crop yields under stressed conditions driven by nanozymes is undergoing an era of continuous breakthroughs due to their superior advantages, such as high efficiency, low-cost, excellent stability, and high designability. However, some unneglectable points are still deserving our attention in future research, which mainly include the biosafety and size of nanozymes, and the exploitation of nanozyme-linked multitechnologies.

Agrofoods quality control. Nanozymes with multiple catalytic activities have also played a significant role in the control of global agrofood quality safety, involving agrofood processing, storage, and monitoring. The agrofood quality safety safeguarded by nanozymes can be summarized as two important pathways: (1) nanozymes with all kinds of catalytic activities can directly regulate the growth of microorganisms to maintain the freshness and prolong the shelf life of agrofood; (2) nanozymes with multiple practical catalytic reactions can be used to monitor the quality change of agrofood in real time.

Microbial contamination is one of the most important factors that threatens global agrofood security. Nanozymes with antibacterial performance can be grafted with agrofood packaging technology to address this global crisis, such as spray coating and biofilm methods. Ce-UiO-66 NPs with excellent oxidase-mimicking and apyrase-mimicking activities have been sprayed to coat on the green carboxymethyl cellulose nanofibers for fruit preservation by poisoning foodborne pathogens through ROS generation and energy consumption, achieving killing efficiency up to 90.46% [8]. Moreover, the Fe_3O_4@PVP@MIL-88B(Fe)-NH-lysozyme/carvacrol nanozymes possessed various preeminent characteristics to combat bacteria, such as bacterial capture, magnetic assembly, lysozyme hydrolysis, light-triggered thermal generation, and carvacrol release, which could completely inactivate both *Staphylococcus aureus* and *Escherichia coli* at a concentration of 10^6 CFU/mL, accelerating the exploitation of innovative agrofood preservation technologies [9]. In addition, nanozymes have also been used in the fabrication of combating bacterial biofilms to preserve agricultural and sideline products [10].

Nanozyme-enabled active packaging engineering can be confirmed as powerfully versatile agrofood preservation technologies in the new era owing to its specialized merits, such as the above-mentioned advantages of nanozymes, improved packaging properties, and various antibacterial activities. Whereas, some research directions are worth noting to walk out the stride forward of nanozyme-enabled agrofood preservation technologies, such as biosafety, catalytic applicability, and integration into films.

Nanozymes possessing multiple useful catalytic reactions can be explored for the signal transduction and amplification elements, thus realizing the rapid, on-site, facile and low-cost real-time monitoring of agrofood quality is the last crucial link to ensure the agrofood safety [11]. The substrates of nanozymes could be regulated by analytes for the sensing of agrofood quality. Horseradish peroxidase and catalytic substrate were encapsulated in zeolite imidazolate frameworks-8 on the crop leaves, petioles, or roots to detect exogenous/endogenous hydrogen peroxide for the monitoring of crop health, achieving a remarkable limit of detection (LOD) as low as 120 nmol/L and various advantages, such as nondestructive, minimally invasive, and capable of real-time and *in situ* analysis, which could strongly reinforce with agrofood safety [12]. The catalytic activity of nanozymes could be regulated by analytes for the sensing of agrofood quality. Different heteroatom-doped graphenes were fabricated as nanozymes sensor arrays on the basis of different pesticides could mask their peroxidase-like activities, which realized the successful discrimination of five pesticides in a concentration range from 5 to 500 μmol/L, and demonstrated various superiorities, including high sensitivity and specificity, high throughput, and good feasibility [13]. Moreover, nanozymes could be modified by bioactive molecules for the universal and specific nanozyme-enabled agrofood quality sensing. Enzyme could be spatially encapsulated with metal–organic frameworks as enzyme-mimicking labels in enzyme-linked immunosorbent assay (ELISA) for agrofood quality, exhibiting various improved advantages in catalytic activity, utilization efficiency of enzyme, and interaction between substrate molecules and nanozymes, which reached an ultrasensitive LOD as low as 8.0 pg/mL and improved the sensitivity by 160-fold than that of standard ELISA [14]. Moreover, bioactive molecules modified nanozymes could be integrated into point-of-care testing devices for agrofood quality. Our group has designed nanozymes modified by antibodies to develop an immunochromatographic strip for agrofood quality, showing various superiorities of rapid, facile, highly programmable, low-cost, and highly sensitive, which realized a sensitive LOD of 0.172 ng/mL in the detection range of 0–6 ng/mL [15].

Nanozyme-encoded on-site detection technologies can be serve as a new generation of rapid agrofood quality control method due to its mighty advantages, such as rapid, user-friendly, and low-cost. However, the enzyme-like activity, enzyme-mimicking types, and integrated device of nanozymes should be paid more attention in the future researches.

To date, nanozymes have great potential to accelerate the enormous success in the management and augmentation of agrofood production, while the limitations in biosafety, activity deficiencies, or type diversity of nanozymes deserve more consideration in the new era of agrofood systems, and these challenges have been discussed in the Supplementary materials (Note S1 online).

In summary, nanozymes, as nature-inspired enzyme mimics with low cost, high designability, and environmental durability, are expected to paint a bright future for the coming era of agrofood systems.

Conflict of interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary materials

Supplementary materials to this news & views can be found online at https://doi.org/10.1016/j.scib.2023.02.011.

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