

Open Access**Article Information****Received:** February 12, 2025**Accepted:** February 25, 2025**Published:** February 28, 2025**Keywords**

Nanotechnology,
Nano-fertilizer,
Heat stress,
Climate change,
Sustainable agriculture,
Crops.

Authors' Contribution

MNI designed; MNI, AA and MIS wrote and revised the paper.

How to cite

Ashraf, A., Iqbal, M.N., Shahzad, M.I., 2025. The Potential of Nano-fertilizers to Mitigate Heat Stress in Crops under Ongoing Climate Change. *Int. J. Mol. Microbiol.*, 8(1): 23-31.

***Correspondence**

Asfa Ashraf

Email:

sundausnaeem@yahoo.com

Possible submissions[Submit your article](#) 

Scan QR code to visit
this journal.

©2025 PSM Journals. This work at International Journal of Molecular Microbiology; ISSN (Online): 2617-7633, is an open-access article distributed under the terms and conditions of the Creative Commons Attribution-Non-commercial-NoDerivatives 4.0 International (CC BY-NC-ND 4.0) licence. To view a copy of this licence, visit <https://creativecommons.org/licenses/by-nc-nd/4.0/>.

INTRODUCTION

Climate change-induced heat stress poses a critical threat to global maize productivity, jeopardizing food security. Long-term variations in meteorological factors including rainfall, temperature, wind, humidity, and others are referred to as climate change (Hurlimann *et al.*, 2021; Iqbal and Ashraf, 2023). Climate change is considered a worldwide hazard that affects crop productivity and food security (Oyelami *et al.*, 2023; Siddique *et al.*, 2024), as well as soil, water, and energy resources (Li, 2023; Ohta and Barrett, 2023), the overall bioeconomy (Peeters *et al.*, 2024), and our ability to fulfill the United Nations' Sustainable Development Goals (Dannevig *et al.*, 2022; Liu *et al.*, 2023). Although climate change is projected to boost the production of various crops in some regions, the general pattern is a negative influence on productivity, particularly in areas with a high human density (Brevik, 2013). Global climate change-related issues include heat stress, reduced food production, altered rainfall patterns, and a shortage of water for irrigation (Iqbal and Ashraf, 2023; Mirón *et al.*, 2023).

Heat stress and agricultural productivity

The term "heat stress" frequently describes a situation in which plants and other organisms are exposed to high temperatures (typically $>35^{\circ}\text{C}$) for an extended length of time, irreversibly changing their capacity to develop properly. For most crops and other creatures, the ideal temperature range is between 20 to 30°C (El-Ramady *et al.*, 2024). Plants can undergo thermos-morphogenesis at warm temperatures, although heat acclimation brought on by high temperatures has detrimental consequences on growth and development (Kan *et al.*, 2023). There is a relationship between climate change and heat stress. Extreme weather events are a major source of fatalities and damage to infrastructure worldwide, and they have risen due to climate change (Newman and Noy, 2023). Various agricultural pursuits rely on meteorological factors that may jeopardise regional and worldwide food security. Consequently, it is imperative to maintain agricultural productivity in the face of climate

change. This can be accomplished by using techniques like (i) agronomic management, which relies on crop, soil, and water factors; (ii) crop genetic improvements to create tolerance to heat and other stresses; and (iii) nano-farming approaches (Wu *et al.*, 2023). Nanomaterials like carbon nanotubes (CNTs), SiO₂-NPs, and TiO₂-NPs may sequester CO₂, which lowers GHG emissions (mostly CO₂) (Younis *et al.*, 2023). Numerous nanomaterials can help plants become more resilient to abiotic stressors and phyto-diseases, which will indirectly slow down climate change (Zhao *et al.*, 2024).

Heat stress tolerance in crops

Crop growth and development may be disrupted or harmed by certain conditions. Among them are thermal injuries, or strains brought on by unfavourable temperatures, such as chilling injuries ($0\text{--}12^{\circ}\text{C}$), freezing injuries ($<0^{\circ}\text{C}$), and heat stress injuries ($>35^{\circ}\text{C}$). Elevated temperatures disrupt physiological and biochemical processes in maize, impairing growth, nutrient uptake, and yield (Li *et al.*, 2022). Over the next ten years, the global surface temperature is predicted to rise by an average of 0.3°C , with the goal being to limit the total increase to below 2°C compared to pre-industrial levels (Hoshikawa *et al.*, 2021). Heat stress can lead to irreversible damage to plant functions or development. Several responses have been recorded, including changes at morpho-biochemical, physiological, and molecular levels (Dos Santos *et al.*, 2022; Mondal *et al.*, 2023). Heat stress may significantly lower crop yields and decrease the production of vital minerals, protein, fibre, and starch (Ahmad *et al.*, 2022). Heat stress can affect maize, especially during the early phases of grain filling and reproduction. It's interesting to note that related environmental covariates including humidity, vapour pressure deficit, soil moisture content, and solar radiation all have a significant influence on how heat stress affects crops. Therefore, heat stress tolerance is seen as a complicated feature, which involves numerous layers of controls in plants (Djalovic *et al.*, 2024).

The development of crop varieties that can withstand heat stress requires an urgent understanding of the relationships between genes (genomics), proteins (proteomics), ions (ionomics), metabolites (metabolomics), transcripts (transcriptomics), and phenotypes (phenomics) and the stress of interest (Bhardwaj *et al.*, 2021; Zaynab *et al.*, 2018). Some of the effects of heat stress on maize plants include delayed blooming, reduced plant height, and decreased leaf area. Moreover, ROS produced by heat stress damages cell membranes and interferes with enzyme activity, which eventually results in reduced plant growth and production. Effective irrigation, nitrogen management, and early maize planting can all assist lower soil temperatures, improve water usage efficiency, and lessen heat stress. Mitigating the negative effects of heat stress in maize farming also requires the deployment of heat-resistant maize cultivars and enhanced breeding methods (Poudela *et al.*, 2023).

Fertilizer use and environmental sustainability

Fertilizer application is required to maintain soil productivity by continuously replenishing plant nutrients (Arshad, 2017; Asadu *et al.*, 2024; Majeed *et al.*, 2017; Sattar and Ikram, 2023). Conventional fertilizers, though widely used, often fail under such stress due to poor nutrient-use efficiency and environmental losses. Excessive or uncontrolled fertilizer usage can harm soil microorganisms and deteriorate soil qualities including osmolarity and water-holding capacity (Govil *et al.*, 2024). Farmers and gardeners can manage soil fertility more effectively if they are aware of the various fertilizer kinds and how they affect the soil. Through the proper fertilizer selection, they can safeguard the environment and maximise crop growth and harvests. Therefore, maintaining the long-term sustainability of our food system while reducing the ecological impact of agriculture requires finding a balance between fertilizer use and environmental sustainability (Asadu *et al.*, 2024).

Recent advancements in the use of nanotechnology in agriculture, plant mineral

nutrition, soil health, and interactions with soil microflora have led to sustainable solutions by substituting traditional bulk fertilizers with their nanoparticulate counterparts, which have superior properties. This will help reduce fertilizer waste, increase crop yield, improve bioavailability and uptake of minerals, and protect the environment. Numerous crops, including maize, common beans, and sunflower, have been shown to have improved germination and seedling growth, as well as physiological activities, when exposed to nanoparticles and nanotubes. This suggests that these materials may be used to increase crop yields. In order to appropriately assess progress and create a sustainable future, the development and enhancement of fertilizers at the nanoscale have the potential to significantly affect energy, the economy, and the environment (Adhikari and Ramana, 2019).

In the modern period, one of the biggest difficulties is maintaining global food security and attaining sustainable agricultural output (Iqbal, 2020a; Iqbal, 2020b). Crop productivity around the world is under danger due to the growing effects of climate change and environmental stresses like drought, salinity, and heavy metal exposure. The application of nanotechnology, in particular nanoparticles (NPs), is a novel way to improve crop resilience and agricultural sustainability. A high surface-area-to-volume ratio and the capacity to enter plant tissues are two of NPs' unique physicochemical characteristics, which improve photosynthetic efficiency, stress tolerance, and nutrient uptake. NPs' ability to increase plant stress tolerance by activating defence systems, enhancing growth under stress, and raising agricultural productivity is the primary focus. NPs have shown promise in tackling important issues in agriculture, including nutrient leaching, dwindling soil fertility, and decreased crop yields brought on by inadequate water management. NPs should be combined with precision agricultural technology to lessen the effects on land and water. Even though further study is required to evaluate their benefits and resolve issues, NPs offer a viable and affordable strategy for improving food security going forward (Cao *et al.*, 2025).

Nano-fertilizers for better crop yield

Nanomaterials have the potential to increase agricultural output through better nutrient delivery, pest management, and crop stress tolerance (Ijaz *et al.*, 2023). Nanotechnology offers intriguing uses that might support food security and sustainable development if applied appropriately (Iqbal, 2022; Iqbal *et al.*, 2018). Additionally, using nano fertilizers, commonly referred to as "nano-biofertilizers," may greatly reduce environmental risks. Numerous studies suggest that nano fertilizers may boost crop yields by encouraging root germination, nitrogen metabolism, photosynthesis, protein and carbohydrate synthesis, and stress tolerance (Ahanger *et al.*, 2021). Apart from the various benefits, they must be applied to the soil in a comparatively small amount, which makes application easier and lowers transportation expenses (Verma *et al.*, 2023).

Nano-fertilizers with enhanced bioavailability and multifunctional properties offer a revolutionary solution. Nano-farming refers to the application of nanomaterials (NMs) or nanoparticles (NPs) in agricultural production (El-Ramady *et al.*, 2023). This may be done in a variety of ways, for as by nano-priming seeds to boost germination by controlling ROS (Kandhol *et al.*, 2022), nano-fertilization to upsurge crop productivity during the growing season (Kumar *et al.*, 2023), nano-pesticide application for plant protection (Shen *et al.*, 2023), nano-sensors to support smart farming (He *et al.*, 2023), nano-harvest (Sári *et al.*, 2023) or nano-postharvest (Wang *et al.*, 2023) applications to prevent food from spoiling and plant nanobionics to improve or alter plant functions (Vithanage *et al.*, 2023). Nanomaterials known as nanofertilizers (NFs), or smart fertilizers, are added to conventional fertilizers to increase crop yields. NFs are made up of nanoscale particles, which are typically less than 100 nanometres. Usually, they consist of organic substances like humic acid or chitosan, or metal or metal oxide nanoparticles like iron or zinc oxide. These particles are intended to improve plant absorption and utilisation by delivering nutrients to the plant in a more efficient and effective manner. Farmers and backyard growers will commercialise NFs as

they become more accessible and favoured. NFs are currently manufactured on a modest scale and have limited commercialisation opportunities (Dimkpa and Bindraban, 2017).

Effective use of natural resources without harming the environment has prompted nanotechnology to emerge as a viable option in a variety of fields, including agricultural management (Awad *et al.*, 2019; Iqbal *et al.*, 2019; Iqbal *et al.*, 2021). The combination of many abiotic pressures presents issues for agriculture, where nanotechnology might help with potential applications. The use of nanoparticles and nanomaterials has a positive impact on crop productivity through a variety of strategies, including green synthesis of nanoparticles, plant-specific protection through the application of nanoherbicides and nanofungicides, precise and consistent nutrient delivery through nanofertilizers, and tolerance to abiotic stress (such as low or high temperatures, drought, salinity, low or high light intensities, UV-B, and metals in soil) through a number of mechanisms, including the activation of the antioxidant enzyme system, which reduces oxidative stress (Djalovic *et al.*, 2024; Iqbal, 2024).

Nano-fertilizers, while promising, require optimization for heat stress-specific challenges, such as improved nutrient delivery, antioxidant support, and stress signaling modulation. Nano-fertilizers (NFs) as an affordable substitute for common chemical fertilisers can boost food output worldwide in a sustainable manner. In addition to being composed of nutrients and micronutrients, NFs may also serve as nutrition transporters. Apart from a delayed release, the nanocarriers transport the nutrients to the proper location, lowering the extra quantity of active compounds deposited in the plant. The materials coated with nanoparticles seem to be able to create holes and enter the vascular system, even if they are able to pass past the stomata with a size exclusion limit larger than 10 nm (Avila-Quezada *et al.*, 2022).

Current agricultural development has established standards for enhancing nutritional quality and lowering the hazardous build-up of

agricultural chemicals in order to guarantee food safety. Food security and sustainable agriculture facilitated by nanotechnology are being investigated more and more as a new area of study. By giving the inorganic nutrients that plants require, enhancing the process by which plants make organic nutrients, and lowering the amount of fertiliser used while guaranteeing plant uptake, nano-fertilizers have the potential to be more effective than conventional fertilisers. In addition to nano-fertilizers, other applications of nanotechnology in agriculture have an impact on crop yield and nutrient quality (Sun *et al.*, 2022). The use of NPK nano-fertilizer increased the plant growth rates and the efficiency of the photosynthesis process in producing dry matter, as well as the speed at which it was transferred from sources to receptors. This resulted in an increase in the components of the yield, which in turn increased the plant's grain yield (Hussein and Ahmed, 2023).

Nano fertilizers have a great potential to improve nutrient usage efficiency, which makes them beneficial for nutrition management. The analysis of variances revealed that all of the features under study were significantly impacted by stress, nitrogen (urea), and nanochelated nitrogen. To summarise, the application of 41 kg.ha⁻¹ nano chelated nitrogen fertilizer, as opposed to urea, resulted in a 4% increase in Rwc, 3% ion leakage, 52% protein, 26% phosphor, 6% potassium, 6% remobilization, and 21% photosynthetic rate in contrast to the control (Astaneh *et al.*, 2021). Since biofertilizers are made industrially from a specific community of microorganisms that either form a mutually beneficial relationship with plants or are a part of their rhizosphere, they have thus emerged as a safer supplement to boost crop production without endangering the environment. Significant opportunities for customising the manufacture of nanofertilizers are suggested by nanotechnology. In order to increase plant production and reduce environmental pollutants, they are usually coated with a desired chemical composition that has controlled release and targeted delivery of efficient nanoscale components. A new path to the nanorevolution would be opened by the research, which would also provide valuable information about the

introduction of various nanoparticle forms in the agricultural industry (Fatima *et al.*, 2021).

The study assessed eight nitrogen application treatment combinations using zero tillage and rice residue retention using foliar sprayed nano urea (4% N) and traditionally applied urea (46% N). Based on the results, the application of 150 kg N/ha improved growth, physiological indices, yield, and quality criteria. Based on the findings, it can be said that, in comparison to farmers' practices (T3), spraying 150 kg N/ha in three equal splits as a basal and right before the first and second irrigations under conservation agriculture, as well as a single application of nano urea (4% N) 60–65 days after sowing, can enhance growth, yield attributes, wheat yield, and NUE (Kumar *et al.*, 2023).

The main benefits of applying nano-microfertilizers to maize include increased grain filling, antioxidant enzyme activity, stomatal opening control, root growth, and chlorophyll retention, all of which increase yield. Nano micro fertilizer in the right form and dosage has a good impact on maize's development of drought resistance and stay-green character. Nano-micronutrients are essential for maintaining cellular homeostasis, controlling physiological processes, and lowering oxidative stress in drought-stricken environments (Vaishnavi *et al.*, 2025).

It is difficult for beginners to the sector because of the high cost and specialised equipment required for NF manufacturing. Newcomers to the business find it difficult due of the high cost and specialised equipment required for NF manufacturing. Furthermore, NFs are not available in a number of nations since there are no rules or laws in place.

CONCLUSION

This exploration bridges nanotechnology, crop physiology, and climate resilience, offering scientific innovation, societal impact and policy relevance for adopting nano-enabled agriculture under climate change. By integrating nanotechnology with crop science, this study

aims to revolutionize heat stress management in crops, ensuring sustainable yields in a warming world. The study will advance precision agriculture and inform global strategies for climate-resilient food systems. It may be determined that micronutrient in the form of nanoparticles have a bright future as a nano-fertilizer in the agriculture for applications based on nano-biotechnology.

CONFLICT OF INTEREST

The author hereby declares no conflict of interest.

REFERENCES

Adhikari, T., Ramana, S., 2019. Nano fertilizer: its impact on crop growth and soil health.

Ahanger, M.A., Qi, M., Huang, Z., Xu, X., Begum, N., Qin, C., Zhang, C., Ahmad, N., Mustafa, N.S., Ashraf, M., 2021. Improving growth and photosynthetic performance of drought stressed tomato by application of nano-organic fertilizer involves up-regulation of nitrogen, antioxidant and osmolyte metabolism. *Ecotoxicol. Environ. Saf.*, 216: 112195.

Ahmad, M., Imtiaz, M., Shoib Nawaz, M., Mubeen, F., Imran, A., 2022. What did we learn from current progress in heat stress tolerance in plants? Can microbes be a solution? *Front. Plant Sci.*, 13: 794782.

Arshad, I., 2017. Effect of different levels of water soluble NPK (20-20-20) fertilizer on the growth and yield of white radish (*Raphanus sativus* L.). *PSM Biol. Res.*, 2(2): 74-78.

Asadu, C.O., Ezema, C.A., Ekwueme, B.N., Onu, C.E., Onoh, I.M., Adejoh, T., Ezeorba, T.P.C., Ogbonna, C.C., Otuh, P.I., Okoye, J.O., Emmanuel, U.O., 2024. Enhanced efficiency fertilizers: Overview of production methods, materials used, nutrients release mechanisms, benefits and considerations. *Environ. Poll. Manag.*, 1: 32-48.

Astaneh, N., Bazrafshan, F., Zare, M., Amiri, B., Bahrani, A., 2021. Nano-fertilizer prevents environmental pollution and improves physiological traits of wheat grown under drought stress conditions. *Sci. Agropec.*, 12(1): 41-47.

Avila-Quezada, G.D., Ingle, A.P., Golińska, P., Rai, M., 2022. Strategic applications of nano-fertilizers for sustainable agriculture: Benefits and bottlenecks. *Nanotechnol. Rev.*, 11(1): 2123-2140.

Awad, A.M., El-Abbasi, I.H., Shoala, T., Youssef, S.A., Shaheen, D., Amer, G.A.E.-A., 2019. PCR and nanotechnology unravelling detection problems of the seed-borne pathogen *Cephalosporium maydis*, the causal agent of late wilt disease in maize. *Int. J. Nanotechnol. Allied Sci.*, 3(1): 30-39.

Bhardwaj, A., Devi, P., Chaudhary, S., Rani, A., Jha, U.C., Kumar, S., Bindumadhava, H., Prasad, P.V., Sharma, K.D., Siddique, K.H., 2021. 'Omics' approaches in developing combined drought and heat tolerance in food crops. *Plant Cell Rep.*, 1-41.

Brevik, E.C., 2013. The potential impact of climate change on soil properties and processes and corresponding influence on food security. *Agric.*, 3(3): 398-417.

Cao, Y., Turk, K., Bibi, N., Ghafoor, A., Ahmed, N., Azmat, M., Ahmed, R., Ghani, M.I., Ahanger, M.A., 2025. Nanoparticles as catalysts of agricultural revolution: enhancing crop tolerance to abiotic stress: a review. *Front. Plant Sci.*, 15: 1510482.

Dannevig, H., Korsbække, M.H., Hovelsrud, G.K., 2022. Advancements of sustainable development goals in co-production for climate change adaptation research. *Climate Risk Manag.*, 36: 100438.

Dimkpa, C.O., Bindraban, P.S., 2017. Nanofertilizers: new products for the industry? *J. Agric. Food Chem.*, 66(26): 6462-6473.

Djalovic, I., Kundu, S., Bahuguna, R.N., Pareek, A., Raza, A., Singla-Pareek, S.L., Prasad, P.V.V., Varshney, R.K., 2024. Maize and heat stress: Physiological,

genetic, and molecular insights. *Plant Gen.*, 17(1): e20378.

Dos Santos, T.B., Ribas, A.F., de Souza, S.G.H., Budzinski, I.G.F., Domingues, D.S., 2022. Physiological responses to drought, salinity, and heat stress in plants: a review. *Stresses.*, 2(1): 113-135.

El-Ramady, H., Abdalla, N., Sári, D., Ferroudj, A., Muthu, A., Prokisch, J., Fawzy, Z.F., Brevik, E.C., Solberg, S.Ø., 2023. Nanofarming: Promising solutions for the future of the global agricultural industry. *Agron.*, 13(6): 1600.

El-Ramady, H., Prokisch, J., El-Mahrouk, M.E., Bayoumi, Y.A., Shalaby, T.A., Brevik, E.C., Solberg, S.Ø., 2024. Nano-Food Farming Approaches to Mitigate Heat Stress under Ongoing Climate Change: A Review. *Agric.*, 14(5): 656.

Fatima, F., Hashim, A., Anees, S., 2021. Efficacy of nanoparticles as nanofertilizer production: a review. *Environ. Sci. Poll. Res.*, 28(2): 1292-1303.

Govil, S., Van Duc Long, N., Escribà-Gelonch, M., Hessel, V., 2024. Controlled-release fertiliser: Recent developments and perspectives. *Ind. Crops Prod.*, 219: 119160.

He, J., Li, J., Gao, Y., He, X., Hao, G., 2023. Nano-based smart formulations: A potential solution to the hazardous effects of pesticide on the environment. *J. Hazard. Mater.*, 456: 131599.

Hoshikawa, K., Pham, D., Ezura, H., Schafleitner, R., Nakashima, K., 2021. Genetic and molecular mechanisms conferring heat stress tolerance in tomato plants. *Front. Plant Sci.*, 12: 786688.

Hurlimann, A.C., Moosavi, S., Browne, G.R., 2021. Climate change transformation: A definition and typology to guide decision making in urban environments. *Sustain. Cities Soc.*, 70: 102890.

Hussein, S.I., Ahmed, K.K., 2023. Response of some maize genotypes traits (*Zea mays* L.) to Nano NPK fertilizer. *Kirkuk Uni. J. Agric. Sci.*, 14(3): 150-159.

Ijaz, M., Khan, F., Ahmed, T., Noman, M., Zulfiqar, F., Rizwan, M., Chen, J., Siddique, K.H., Li, B., 2023. Nanobiotechnology to advance stress resilience in plants: Current opportunities and challenges. *Mater. Today Bio.*, 22: 100759.

Iqbal, M.N., 2020a. COVID-19 and Locust Infestation: An Acute Food Security Challenge. *PSM Microbiol.*, 5(2): 54-56.

Iqbal, M.N., 2020b. Covid-19 Pandemic: Impact on Agriculture and Food Security in Rural Population. *PSM Biol. Res.*, 5(2): 95-97.

Iqbal, M.N., 2022. Nanoparticles for Improved Diagnostic and Therapeutic Applications. *Int. J. Nanotechnol. Allied Sci.*, 6(2): 41-43.

Iqbal, M.N., 2024. Nanotechnology Awareness: Implications for Public Health and the Environment. *Int. J. Nanotechnol. Allied Sci.*, 8(1): 20-22.

Iqbal, M.N., Ashraf, A., 2023. Global Climate Change Impacts Health, Environment and Economy. *Int. J. Altern. Fuels Energy.*, 7(2): 34-36.

Iqbal, M.N., Ashraf, A., Iqbal, A., 2019. Can Nanotechnology Improve Detection of the Seed-borne Pathogens through PCR? *Int. J. Nanotechnol. Allied Sci.*, 3(2): 50-52.

Iqbal, M.N., Ashraf, A., Iqbal, I., Shahzad, M.I., 2021. A Review of Recent Developments and Future Prospects of Nanomaterials. *Int. J. Nanotechnol. Allied Sci.*, 5(2): 26-30.

Iqbal, M.N., Ashraf, A., Wang, S., 2018. Gold Nanoparticles (GNPs): Synthesis, Properties and Conjugation Methods. *Int. J. Nanotechnol. Allied Sci.*, 2(1): 1-2.

Kan, Y., Mu, X.-R., Gao, J., Lin, H.-X., Lin, Y., 2023. The molecular basis of heat stress responses in plants. *Mol. Plant.*, 16(10): 1612-1634.

Kandhol, N., Singh, V.P., Ramawat, N., Prasad, R., Chauhan, D.K., Sharma, S., Grillo, R., Sahi, S., Peralta-Videa, J., Tripathi, D.K., 2022. Nano-priming: Impression on the beginner of plant life. *Plant Stress.*, 5: 100091.

Kumar, N., Samota, S.R., Venkatesh, K., Tripathi, S., 2023. Global trends in use of nano-fertilizers for crop production: Advantages and constraints—A review. *Soil Tillage. Res.*, 228: 105645.

Li, S.H., 2023. Impact of climate change on wind energy across North America under climate change scenario RCP8. 5. *Atmos. Res.*, 288: 106722.

Li, T., Zhang, X.-p., Liu, Q., Liu, J., Chen, Y.-q., Sui, P., 2022. Yield penalty of maize (*Zea mays* L.) under heat stress in different growth stages: A review. *J. Integr. Agric.*, 21(9): 2465-2476.

Liu, Z., Zhang, Y., Ni, X., Dong, M., Zhu, J., Zhang, Q., Wang, J., 2023. Climate action may reduce the risk of unemployment: an insight into the city-level interconnections among the sustainable development goals. *Resour. Conserv. Recycl.*, 194: 107002.

Majeed, A., Muhammad, Z., Islam, S., Ullah, Z., Ullah, R., 2017. Cyanobacterial application as bio-fertilizers in rice fields: role in growth promotion and crop productivity. *PSM Microbiol.*, 2(2): 47-50.

Mirón, I.J., Linares, C., Díaz, J., 2023. The influence of climate change on food production and food safety. *Environ. Res.*, 216: 114674.

Mondal, S., Karmakar, S., Panda, D., Pramanik, K., Bose, B., Singhal, R.K., 2023. Crucial plant processes under heat stress and tolerance through heat shock proteins. *Plant Stress.*, 10: 100227.

Newman, R., Noy, I., 2023. The global costs of extreme weather that are attributable to climate change. *Nat. Commun.*, 14(1): 6103.

Ohta, H., Barrett, B.F., 2023. Politics of climate change and energy policy in Japan: Is green transformation likely? *Earth Syst. Gov.*, 17: 100187.

Oyelami, L.O., Edewor, S.E., Folorunso, J.O., Abaslim, U.D., 2023. Climate change, institutional quality and food security: Sub-Saharan African experiences. *Sci. Afr.*, 20: e01727.

Peeters, P., Çakmak, E., Guiver, J., 2024. Current issues in tourism: Mitigating climate change in sustainable tourism research. *Tour. Manag.*, 100: 104820.

Poudela, M., Poudelb, M.R., Dhunganab, B., 2023. Effects and Management Practices of Heat Stress in Maize (*Zea Mays* L.): A Review. *i Tech. Mag.*, 5: 22-25.

Sári, D., Ferroudj, A., Muthu, A., Prokisch, J., El-Ramady, H., Elsakhawy, T.A., Omara, A.E.-D., Brevik, E., 2023. Nano-Enabled Agriculture Using Nano-Selenium for Crop Productivity: What Should Be Addressed More? *Env. Biodivers. Soil Secur.*, 7(2023): 85-99.

Sattar, M., Ikram, W., 2023. Influence of Fertilizer Application Method on Phosphorus Availability to Maize Crop in Calcareous Soil. *Int. J. Nanotechnol. Allied Sci.*, 7(2): 24-43.

Shen, M., Liu, S., Jiang, C., Zhang, T., Chen, W., 2023. Recent advances in stimuli-response mechanisms of nano-enabled controlled-release fertilizers and pesticides. *Eco-Environ. Health.*, 2(3): 161-175.

Siddique, K.H., Bolan, N., Rehman, A., Farooq, M., 2024. Enhancing crop productivity for recarbonizing soil. *Soil Tillage. Res.*, 235: 105863.

Sun, Y., Zhu, G., Zhao, W., Jiang, Y., Wang, Q., Wang, Q., Rui, Y., Zhang, P., Gao, L., 2022. Engineered nanomaterials for improving the nutritional quality of agricultural products: A Review. *Nanomater.*, 12(23): 4219.

Vaishnavi, S., Kathirvelan, P., Manivannan, V., Djanaguiraman, M., Thiyyageshwari, S., 2025. Role of nano fertilizers on improving drought tolerance of maize.

Verma, K.K., Song, X.-P., Degu, H.D., Guo, D.-J., Joshi, A., Huang, H.-R., Xu, L., Singh, M., Huang, D.-L., Rajput, V.D., 2023. Recent advances in nitrogen and nano-nitrogen fertilizers for sustainable crop production: a mini-review. *Chem. Biol. Technol. Agric.*, 10(1): 111.

Vithanage, M., Zhang, X., Gunarathne, V., Zhu, Y., Herath, L., Peiris, K., Solaiman, Z.M., Bolan, N., Siddique, K.H., 2023. Plant nanobionics: Fortifying food security via engineered plant productivity. *Environ. Res.*, 229: 115934.

Wang, S.Y., Herrera-Balandrano, D.D., Jiang, Y.H., Shi, X.C., Chen, X., Liu, F.Q., Laborda, P., 2023. Application of chitosan nanoparticles in quality and preservation of postharvest fruits and vegetables: A review. *Compr. Rev. Food Sci. Food Saf.*, 22(3): 1722-1762.

Wu, L., Elshorbagy, A., Helgason, W., 2023. Assessment of agricultural adaptations to climate change from a water-energy-food nexus perspective. *Agric. Water Manag.*, 284: 108343.

Youns, Y.T., Manshad, A.K., Ali, J.A., 2023. Sustainable aspects behind the application of nanotechnology in CO₂ sequestration. *Fuel.*, 349: 128680.

Zaynab, M., Noman, A., Fatima, M., Saleem, T., Abbas, S., Raza, A., Iqbal, M.N., 2018.

Proteomics Approach Reveals Seed Germination Mechanism in Model Plants. *PSM Microbiol.*, 3(1): 30-36.

Zhao, L., Zhou, X., Kang, Z., Peralta-Videa, J.R., Zhu, Y.-G., 2024. Nano-enabled seed treatment: A new and sustainable approach to engineering climate-resilient crops. *Sci. Total Environ.*, 910: 168640.