

Review

Nano-Food Farming Approaches to Mitigate Heat Stress under Ongoing Climate Change: A Review

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Abstract: Increased heat stress is a common feature of global climate change and can cause adverse impacts on crops from germination through maturation and harvest. This review focuses on the impacts of extreme heat (>35 °C) on plants and their physiology and how they affect food and water security. The emphasis is on what can be done to minimize the negative effects of heat stress, which includes the application of various materials and approaches. Nano-farming is highlighted as one promising approach. Heat is often combined with drought, salinity, and other stresses, which together affect the whole agroecosystem, including soil, plants, water, and farm animals, leading to serious implications for food and water resources. Indeed, there is no single remedy or approach that can overcome such grand issues. However, nano-farming can be part of an adaptation strategy. More studies are needed to verify the potential benefits of nanomaterials but also to investigate any negative side-effects, particularly under the intensive application of nanomaterials, and what problems this might create, including potential nanotoxicity.

Keywords: climate change; food security; global warming; nano-agriculture; nanotoxicity; water security



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1. Introduction

Climate change can be defined as long-term changes in climatic parameters such as rainfall, temperature, wind, humidity, and others [1]. Ongoing global climate change has a complicated nature that influences local, national, and regional conditions with economic, social, and environmental consequences [2]. Climate change is considered a worldwide hazard that affects crop productivity and food security [3–6], as well as soil, water, and energy resources [7–10], the overall bioeconomy [11,12], and our ability to fulfill the United Nations' Sustainable Development Goals [13–16]. The rising average global temperature and more frequent extreme thermal events are major concerns with climate change [17].

Heat stress often refers to a period during which plants and other organisms are subjected to high temperatures (normally >35 °C) for long enough to permanently alter their ability to grow in a normal manner. The ideal temperature range for most crops and other organisms is between 20 to 30 °C [18]. Heat stress can damage crops, cattle, poultry, and aquaculture production [19,20]. Heat stress also negatively affects biodiversity [21], life quality in cities [22], and workers' health and productivity [23]. Extreme heat stress events have been recorded in several places around the world, e.g., in species losses in

coastal areas of eastern China [21], projected reduced yields in corn production in the USA [24] and rice yields in southern China [25], and increased problems with human health [26–28]. At warm temperatures, plants can induce thermos-morphogenesis, whereas high temperatures trigger heat acclimation that leads to negative effects on growth and development [29]. These effects involve the production of reactive oxygen species (ROS) that cause damage to cell organelles and membranes, which reduces the assimilation of nutrients and the photosynthetic process [30]. Several approaches have been suggested to address heat stress [31] or related stress mitigations [32]. Recently, nanotechnology has been suggested as one approach [33], an approach we will focus on in this review paper.

Nano-farming refers to the application of nanomaterials (NMs) or nanoparticles (NPs) in agricultural production [34]. This can be performed in different ways, including nano-priming of seeds to increase germination through the regulation of ROS [35], nano-fertilization to increase crop productivity during the growing season [36], nano-pesticide application for plant protection [37], nano-sensors to support smart farming [38,39], nano-harvest [40] or nano-postharvest [41,42] applications to reduce food spoilage, and plant nano-bionics to enhance or modify plant functions [43]. Nanomaterials have the potential to enhance the productivity of crops by improving the delivery of nutrients, managing pest control, and supporting crop stress resilience [44]. Nanotechnology has promising applications that may contribute to sustainable development and food security if used properly.

This review focuses on climate change in agriculture and nano-farming under heat stress. The main goal is to investigate how nano-farming can be used to mitigate heat stress, one of several negative effects of climate change. Management strategies are suggested that can be applied in a systematic way to improve food and water security under heat stress conditions.

2. Climate Change: A Global Issue

2.1. Climate Change Features

Climate change is a global concern with serious consequences for life on our planet (Figure 1; [1]). Climate change is defined as “*periodic modification of Earth’s climate brought about as a result of changes in the atmosphere as well as interactions between the atmosphere and various other geologic, chemical, biological, and geographic factors within the Earth system*” [45]. Climate change adaptation means altering our behavior, systems, and (in some cases) ways of life to protect our families, economies, and the environment in which we live from the impacts of climate change [1]. Common features of climate change include increasing temperatures, elevated atmospheric CO₂ concentrations, and changes in precipitation with more extreme weather events [46]. Climate change has a direct impact on the agricultural sector through temperature fluctuations, flooding, and drought, which may cause significant damage to the productivity of crops [47,48]. At the same time, agriculture, forestry, and land use activities also contribute to climate change, with 18.4% of global greenhouse gas emissions coming from these sectors. Changes in both range and arable land use affect balances of greenhouse gases (GHGs) [7,49]. Although climate change is expected to benefit the production of some crops in some places [3,50], the overall pattern is a negative effect on productivity, particularly in areas with a high population density [3]. Global problems related to climate change include heat stress, a lack of water for irrigation, changes in rainfall patterns, and decreased food production [51]. These impacts can be found in nearly all sectors, including agriculture.

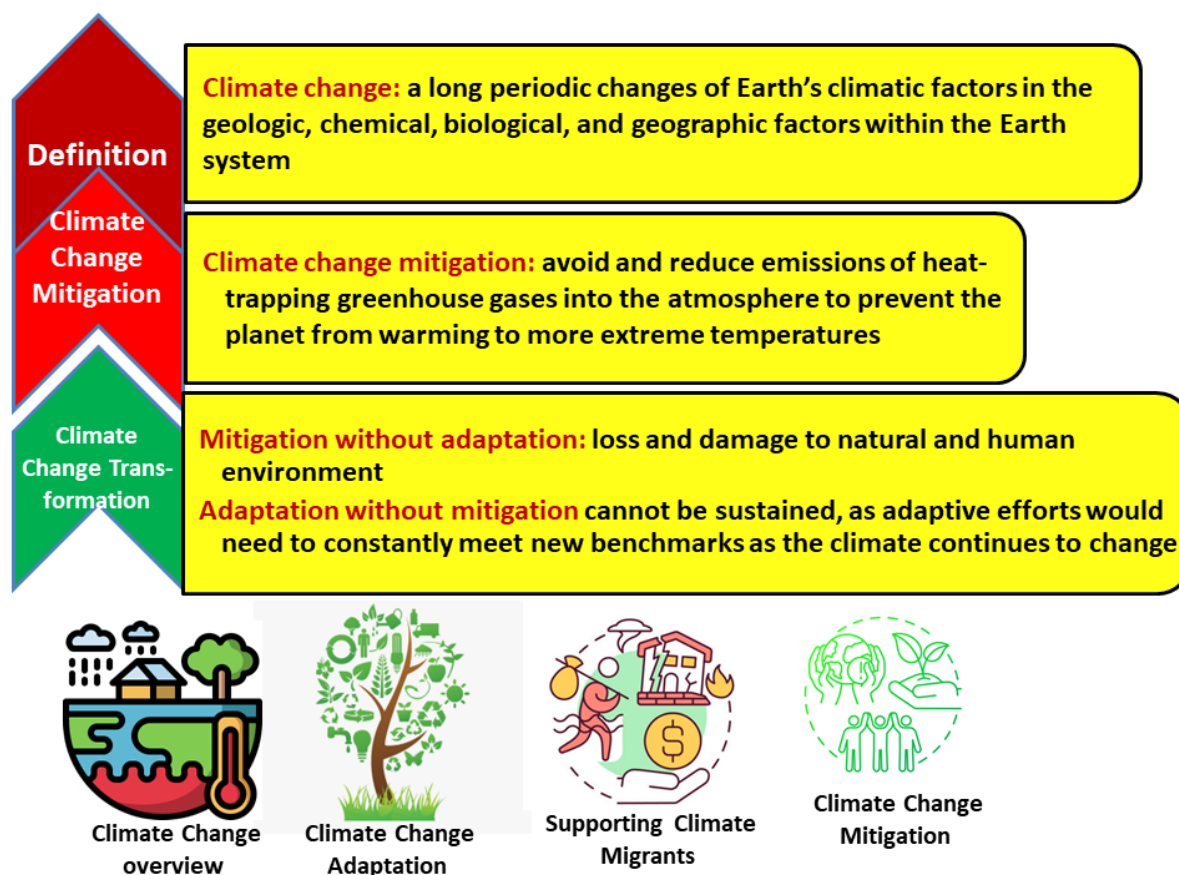


Figure 1. The definitions of major terms associated with climate change [1] (free images from <https://www.flaticon.com/icons>, accessed on 22 September 2023).

2.2. Climate Change Threats

The warming that accompanies climate change leads to the melting of glaciers and polar icecaps, rising sea levels, and increased risks of forest fires, heat waves, droughts, floods, cyclones, hurricanes, and typhoons. These threats lead to food insecurity, climate refugees, a loss of biodiversity, and negative human health effects (Figure 2; [47,48]). There is a need to understand the global climate impacts and their ecological dynamics, to identify hotspots of vulnerability and resilience, and to identify management interventions that may assist biosphere resilience to climate change. On the other hand, greenhouse gas balances are important components of the global carbon and nitrogen cycles [7]. These gases can be absorbed or emitted by lakes [52], oceans [53], livestock [54–56], agricultural and agroforestry systems [55,57], natural terrestrial ecosystems [57,58], and soils [7,55,59]. The main sources of GHGs are CO₂ (74%), CH₄ (17%), and N₂O (9%) (Figure 3; [60]). Recent studies have focused on aspects of the GHG balance, including urban balances [61,62]; climate-smart management to reduce GHGs from agricultural production [63], transportation and energy [64,65]; and GHG reduction strategies for various regions around the world [57,66,67]. Global warming results from the accumulation of GHGs in the atmosphere. This increases the average global temperature due to radiation absorption in the thermal infrared range. These GHGs include carbon dioxide (CO₂), nitrous oxide (N₂O), nitric oxide (NO), ozone (O₃), volatile organic compounds (VOCs), methane (CH₄), and water vapor, as well as industrial GHGs, including hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF₆). GHGs can create irreversible damage to the health of living beings, the ozone layer, and the broader environment [68].

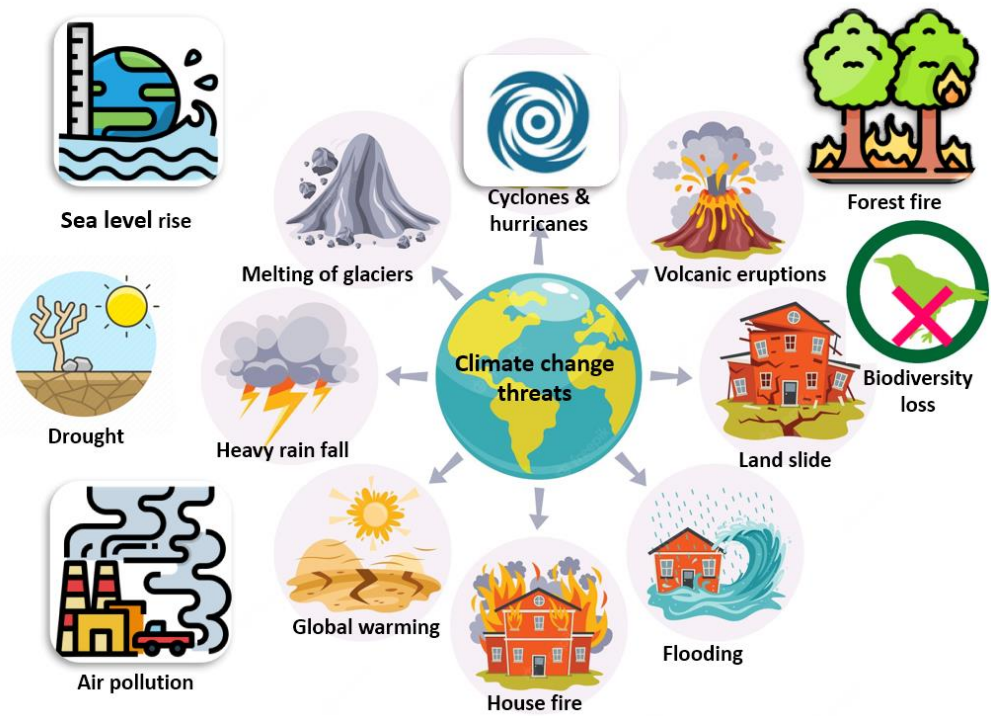


Figure 2. Different threats that can be caused by climate change [47,48] (free images from <https://www.flaticon.com/icons>, accessed on 22 September 2023).

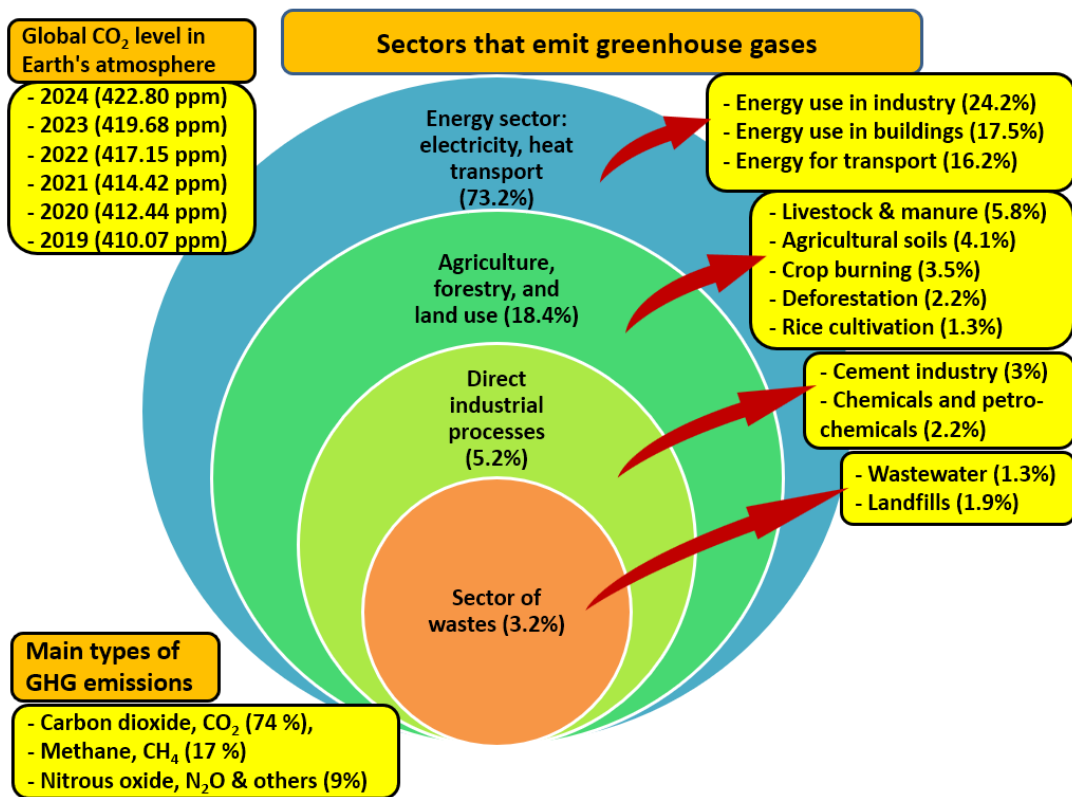


Figure 3. Global sectors that generate greenhouse gases (GHGs) and how much they contribute to GHG emissions [60] (source: <https://www.co2.earth/>, accessed on 10 February 2024).

2.3. Climate Change and Heat Stress

There is a relationship between climate change and heat stress. Temperature is one of the main climatic elements that controls the activities of humans, including farming practices. Increased temperatures as a result of climate change create heat stress for livestock, humans, crops, and the entire ecosystem [19,24,69]. Extreme weather events, which have been increased by climate change, are major causes of loss of life and infrastructure damage all over the world [70]. Thus, heat stress exposure is projected to increase with ongoing climate change. Atmospheric temperature is an important climatic factor that significantly impacts the growth and development of all living organisms (microbes, plants, animals, and humans). At the farm level, the activities of plants, animals, and soil organisms are closely linked to temperature. Studies have shown that seasonal temperature changes have large impacts on growth [71], which has led to changes in vegetation and seawater temperature [72]. For example, the seawater temperature in the coastal zone of the Baltic Sea has increased by 0.2 °C per decade [73], and in the Yangtze River, China, the increase has been 0.40 to 0.52 °C per decade [74]. Increases in temperature also affect urban areas [75], air quality [76], water supply [77], and food security [3], which increase the risks of mortality [78,79].

2.4. Climate Resilient Agriculture

In the absence of climate change mitigation, multiple adverse impacts on agroecosystem resources could include reduced soil fertility; increased soil erosion and pollution of soil, water, and air; a reduction in fish production; increased loss of global biodiversity; and loss of drinking water [80]. Recent studies have examined the benefits of climate-smart agriculture, including reduced GHG emissions and enhanced food security. Hellin et al. [81] argue that climate-smart agriculture has morphed into a platform that focuses on technical aspects at the expense of socio-economic issues and therefore leads to increased social and political vulnerability for low-income farmers. Because of this, they advocate a pivot from climate-smart to climate-resilient agriculture to promote more equitable socio-economic outcomes [81]. Recent studies on climate-resilient agriculture include modelling crop–water–income dynamics [82], examining the role of rhizosphere microorganisms in climate-resilient sustainable plant production [83], climate-resilient agricultural indicators for addressing hunger and poverty [84], knowledge gaps in climate-resilient practices in India [85], and strategies to strengthen the climate-resilient health system [86]. These are only a few examples. Smart technologies for climate-resilient agriculture may include carbon-smart agro-forestry and microbial-smart, water-smart, weather-smart, energy-smart, and knowledge-smart approaches [87].

Climate change can be addressed within farming systems by harnessing soil carbon sequestration as a sustainable solution for environmental challenges [88]. It is important to understand the dynamics of soil organic carbon stock in agro-ecosystems under a changing climate to maintain the productivity of soils and offset GHG emissions [89]. Crop residue return can mitigate the negative effects of climate change on SOC and crop productivity [90,91]. Smart agriculture can be an effective tool in achieving sustainability goals [92]. Climate-smart practices can reduce the energy demand and the emissions of CO₂ [93]. Therefore, there is a need for climate-smart agro-practices for the global adaptation to climate change [94].

2.5. Climate Change and Nano-Farming

This section will explore the role of nanomaterials in combating climate change and the action of nanomaterials under heat stress. Changes in atmospheric CO₂ drive climate change, including changes in temperature, as well as floods, droughts, heat waves, etc. These stressful conditions may be ameliorated with nanomaterials [68,95]. Nanomaterials can reduce GHG emissions (mainly CO₂) via CO₂ sequestration by nanomaterials such as carbon nanotubes (CNTs), SiO₂-NPs, and TiO₂-NPs [95]. Many nanomaterials can indirectly mitigate climate change by increasing plant tolerance to abiotic stress and resistance to

phyto-diseases [96]. These nanomaterials can be classified based on their functionalized chemical groups into the following categories:

- (1) Nanofilms for the electrocatalytic reduction of CO₂ [97];
- (2) Nano-metal organic frameworks (MOFs) as absorbents for GHG sequestration [98];
- (3) Nanofibers as catalysts for the conversion and sequestration of CO₂ [99];
- (4) Nanocomposites for photocatalytic CO₂ reduction and H₂ evolution reactions [100];
- (5) Carbon nanotubes to reduce CO₂ emissions and utilization [101];
- (6) Nano-membranes to combat climate change using hydrogen production as a clean energy source instead of fossil fuels [102];
- (7) Nano-zeolites for CO₂ capture [103];
- (8) Nano-silica to reduce CO₂ emissions [104].

Nano-farming approaches and other strategies can be considered for agro-productivity under the changing climate through the following targets: (1) reducing agricultural production losses under climate change and heat stress, (2) ensuring food security under changing climate and socio-economic environments, and (3) reducing the adaptation consequences to water and energy resources. Several farming activities are dependent on climatic elements that can threaten local and global food security [105]. Therefore, maintaining agricultural productivity under climate change is a critical need that can be achieved through strategies such as (i) agronomic management (depending on soil, water, and crop factors), (ii) crop genetic improvements to create tolerance to heat and other stresses, and (iii) nano-farming approaches (Figure 4; [105]).

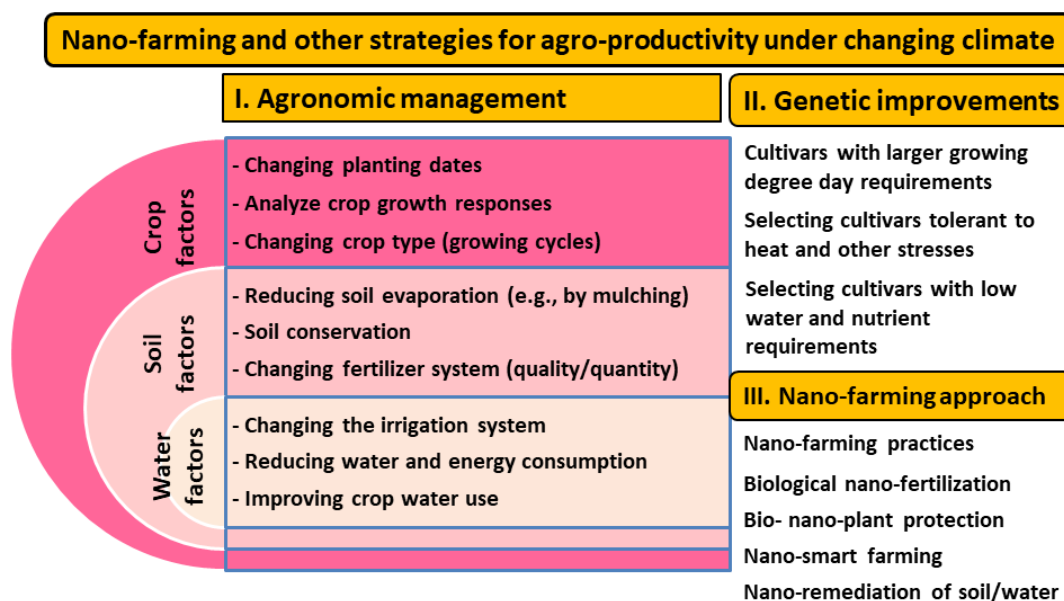


Figure 4. Different strategies for nano-food farming and other approaches that can be utilized for climate change [62,105].

3. Heat Stress and Agroecosystems

3.1. Agroecosystems in a Changing World

Agroecosystems are vital to our modern societies and the global environment [106,107]. Each component of the agroecosystem is affected by climate change and heat stress, including soil [7,108], water [50], microbes [109], plants [110–112], animals [113], and humans [114–116] (Figure 5; [48,109,110]). As examples, these impacts may involve changes in crop phenology, soil moisture content, soil carbon pools, and vegetation respiration, among others. The complexity and diversity of agroecosystems make it hard to quantitatively analyze the overall impacts [117]. Recent studies have focused on topics such as the impacts of climate change and heat stress on soil organic carbon sequestration under lowland rice

cultivation [118], the impact of high temperatures (40 °C) on chickpea production [119], and the ability of biochar to improve *Thymus vulgaris* growth under heat stress (33 °C) [120].

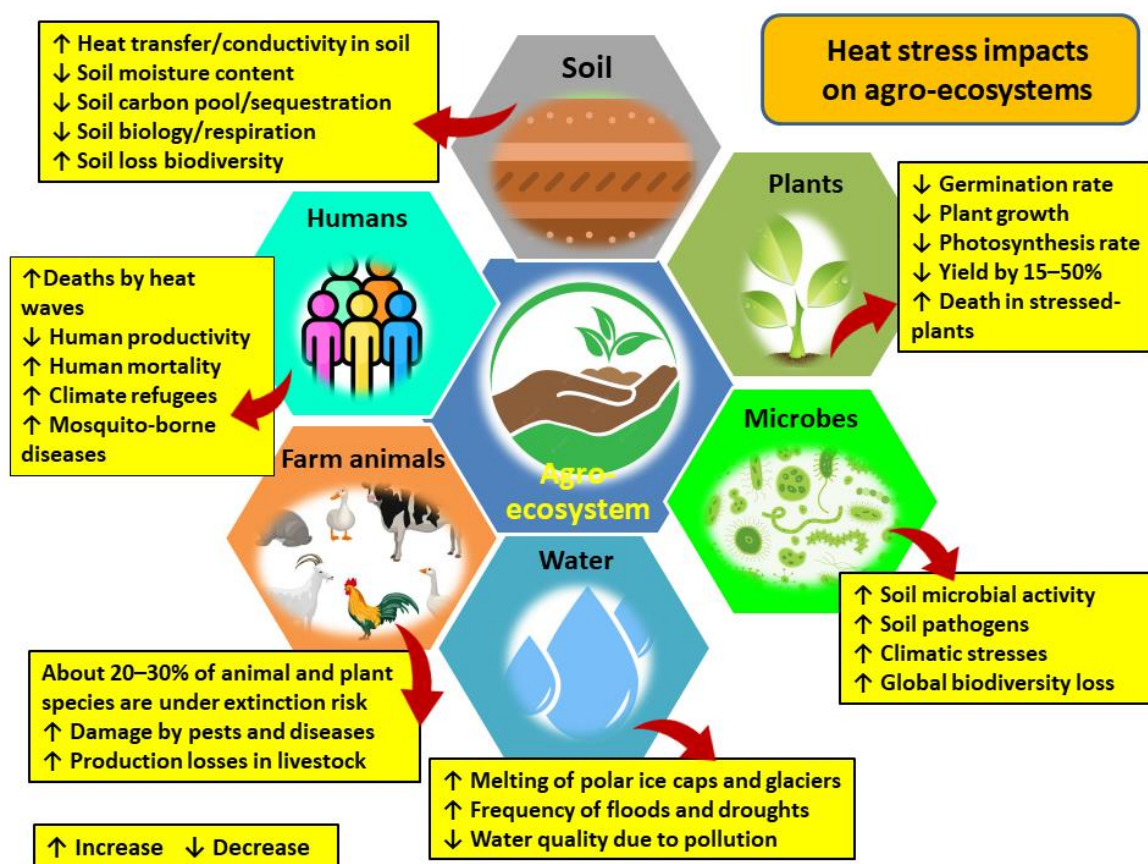


Figure 5. Impacts of heat stress on different agroecosystem components [48,109,110].

3.2. Food Security under Heat Stress

Food security is defined as follows: “food security is achieved when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life” [121]. Increased heat waves linked to climate change threaten global food security over both the short and long term (Figure 6; [121–124]). Society has a major challenge in providing sufficient, nutritious, affordable, and safe food for the global population. Food security was identified as a key issue by organizations like the United Nations FAO [121] during the World Food Summit in 1996. This challenge is still relevant due to ongoing global climate change, degradation of water and land resources, biodiversity loss, and food wastage, which all contribute to food insecurity [125]. Research has addressed several dimensions of food security, including food availability, access to food, utilization and stability of the food systems, and social acceptability of food sources (e.g., [122,123,126]). Global food security is under threat due to factors such as pollution [127,128], drought, and heat stresses [129,130]. Minimizing food waste and proper food management are other important factors in food security [131]. Heat stress impacts food security as it affects wild plant, fish, and animal production, as well as crop, aquaculture, and farm animal production. Studies have documented the negative impacts of heat stress on rice [132], fish [133], and farm animal [20] productivity, respectively. Other examples include “No farmer no food” [134], the interaction between food production and climate change [135], decreased cucurbits production in North Africa due to heat stress [136], decreased salmon production under future climate change [137], food and water insecurity [138], and global

agri-food trade under climate change [139]. Food production includes food processing, transport, sorting, and disposal of food wastes [135].

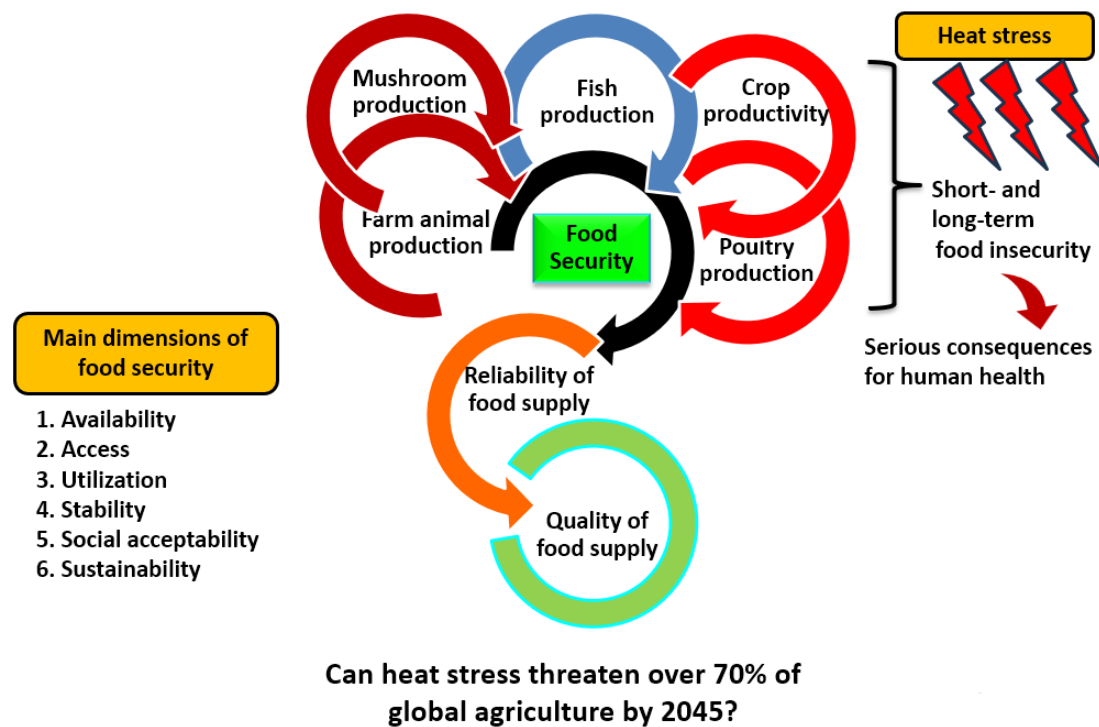


Figure 6. Impacts of heat stress on food security that can cause food insecurity over both short and long terms [121–124].

3.3. Heat Stress and Cultivated Plants

Atmospheric temperature is important for all living organisms. During a plant's life cycle, many stressful situations may occur. Some stresses can cause interruptions or damages in crop growth and development. Among these are stresses caused by unfavorable temperatures (thermal injuries) such as freezing injuries ($<0\text{ }^{\circ}\text{C}$), chilling injuries ($0\text{--}12\text{ }^{\circ}\text{C}$), and heat stress injuries ($>35\text{ }^{\circ}\text{C}$). An average $0.3\text{ }^{\circ}\text{C}$ increase in the global surface temperature is expected in the next decade, while the global target is to keep the overall increase below $2\text{ }^{\circ}\text{C}$ compared to pre-industrial levels [140]. 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 (Figure 7; [17,30,141]). These impacts can cause changes in phenology, increase oxidative stress, inhibit seed germination, cause turgor loss, alter photosynthesis, lower transpiration rates, and reduce biomass and carbohydrate metabolism [141]. Heat stress can cause significant reductions in crop yield and reduce the synthesis of starch, protein, fiber, and essential mineral contents [109]. Yield reductions up to 50% have been reported in onion (*Allium cepa* L.) [142], cotton (*Gossypium hirsutum* L.) [143], and rice (*Oryza sativa* L.) [144]. Plant adaptation to heat stress can be summarized with the following strategies:

- (1) Maintain protein and flower homeostasis and non-coding RNA regulation;
- (2) Minimize cellular damage and enhance antioxidant enzymes;
- (3) Protect heat shock proteins, the formation of buds, and the development of pollen and fruits from dehydration, and delay leaf senescence;
- (4) Promote the photosynthesis rate and antioxidant defenses, and activate defense pathways;
- (5) Regulate heat shock factors, transcription, and epigenetics;
- (6) Utilize heat-tolerant varieties [17,30,141].

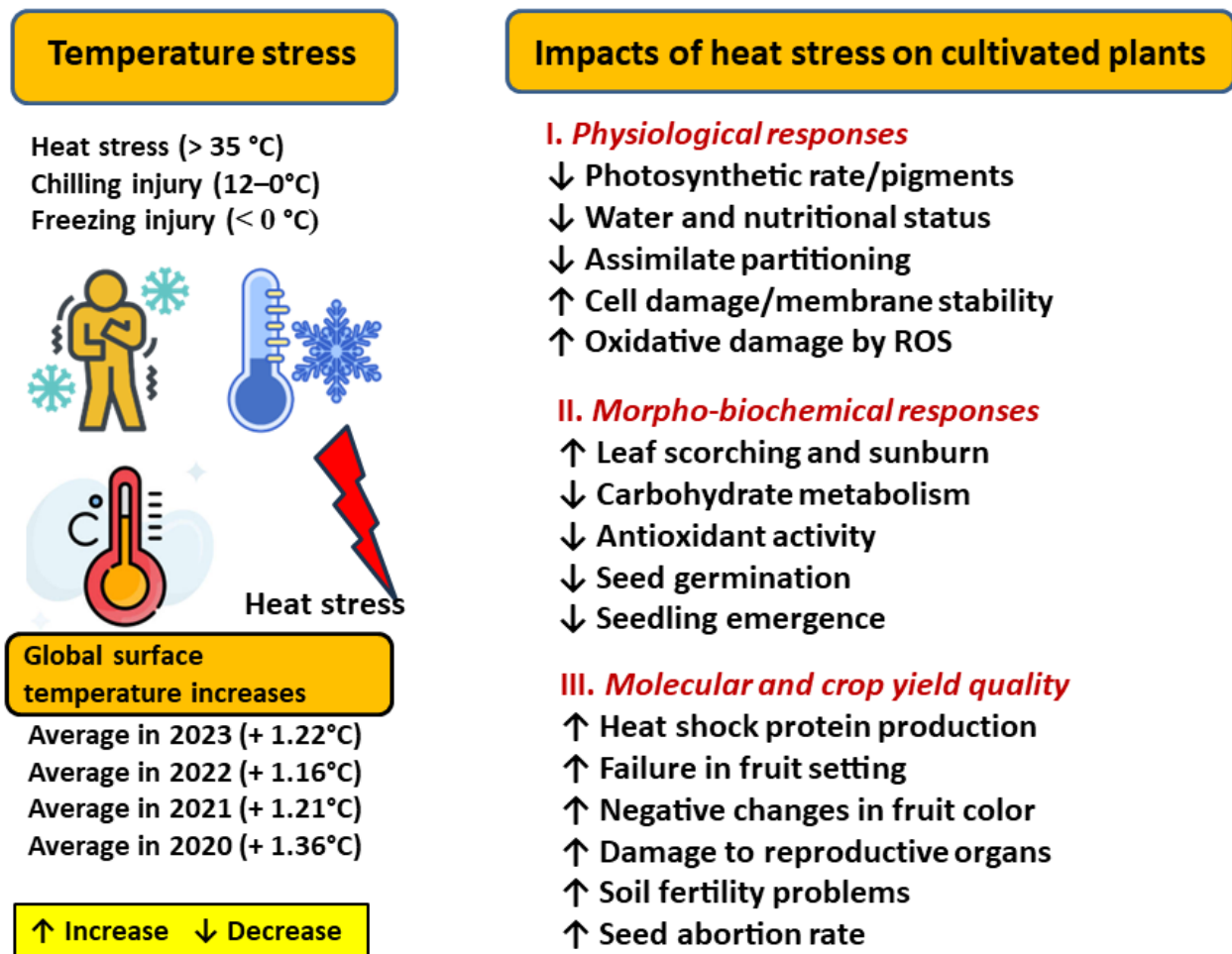


Figure 7. Plant responses to heat stress. The direction of the arrows indicates the positive or negative effects of heat stress on the given plant processes within each of the boxes. Global surface temperature increases are relative to the 20th century average [145].

Thermal stress can cause enormous damage to cell membranes, as well as many plant processes, including triggering oxidative stress, producing ROS, decreasing protein synthesis/metabolism, and altering the production of antioxidants and phytohormones, leading to changes in hormonal homeostasis [17]. In some regions like Egypt, higher temperatures have been recorded in recent years, reaching more than 50 °C and causing catastrophic productivity damage to many crops, including banana and other horticultural crops (Figure 8). Such high temperatures cause heat stress and clearly inhibit crop growth due to sunburned leaves and twigs, senescent leaves, and blotching of fruits and leaves [30]. Generally, the signs of heat stress on plants can be manifested by symptoms such as rolling and cupping of leaves; drying of leaf margins; dropping of flowers and/or fruits, buds and blossoms; premature blooming and bolting; or wilting of the entire plant [18].

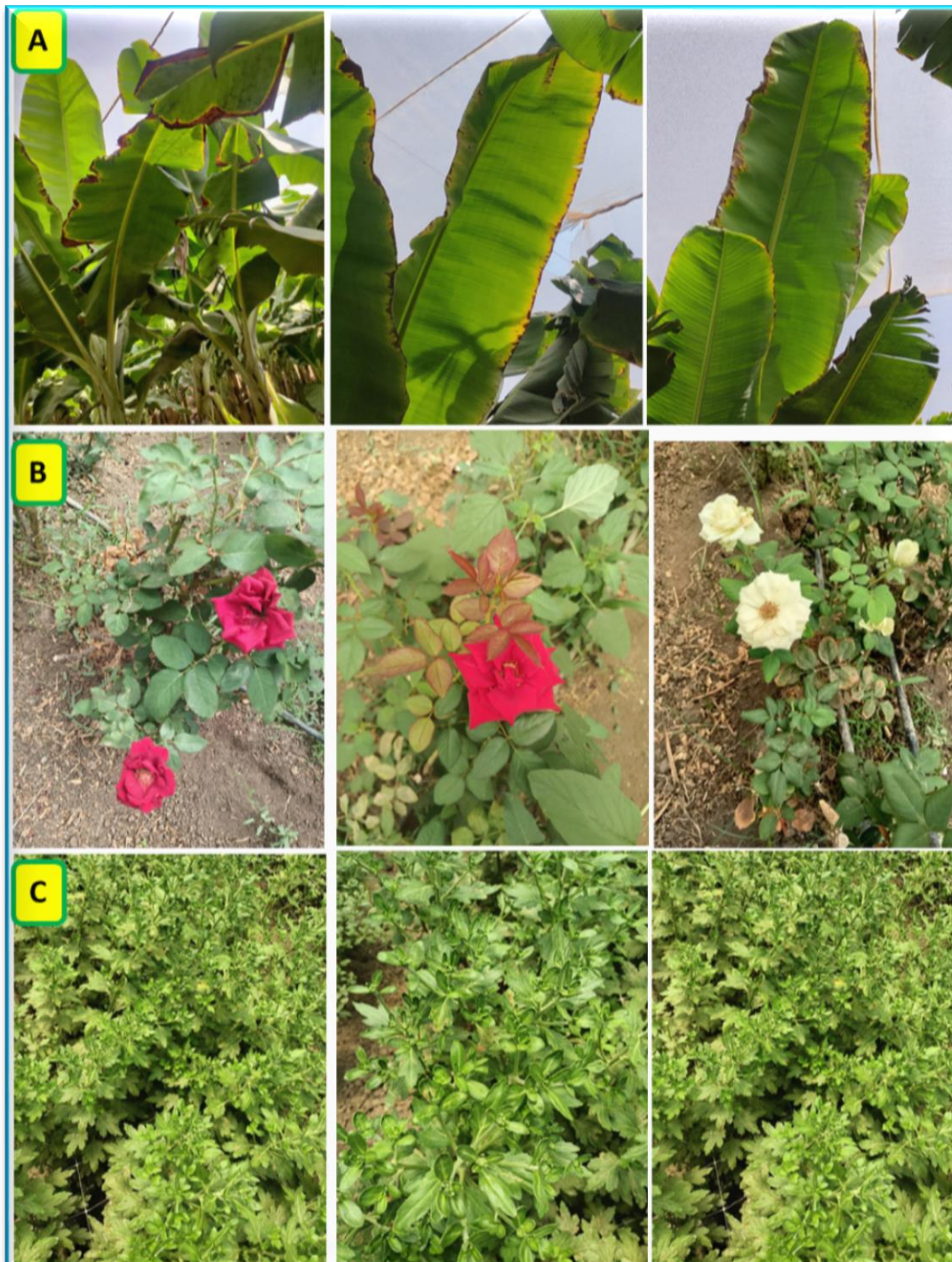


Figure 8. Heat stress on new banana leaves (photos in group (A)), heat stress in rose plants causing deformation of the flowers as a result of a decrease in the number of petals (photos in group (B)), and heat stress on *Chrysanthemum morifolium* plants, which prevents flowering by causing abscission of flower buds (photos in group (C)). These stress symptoms were observed after a period with air temperatures of 45 °C (measured in the shade) during the summer of 2023 in Egypt (photos by M. El-Mahrouk).

3.4. Plant–Pathogen Interactions under Heat Stress

Plant production faces serious challenges due to both climate and pathogen stressors due to the continuous changes in plant pathogens under changing climatic conditions [146]. There is a strong link between heat stress and phytopathogens, where increasing temper-

atures may support the growth and spread of plant pathogens [147]. The role of applied nanomaterials against phytopathogens from one side [148], and to mitigate heat stress from the other [149], is an important global issue due to the impact on crop productivity. Nano-pesticides have received considerable attention for application against individual and combined stresses (e.g., [150–152]). Plant–pathogen interactions also occur under other stresses [153], such as drought [154–156], water stress [157], and elevated atmospheric CO₂ [158].

3.5. Mechanisms of the Plant Response to Heat Stress

Response mechanisms are a promising research area, which include morphological, physiological, biochemical, and molecular mechanisms (e.g., [17,29,30,159]). Research into the plant response to heat stress has included how to reduce the stomatal number and their conductance; how to increase the plant root system; how to decrease leaf folds, curls, and leaf area; and how to reduce water loss via evapotranspiration. Plants under thermal stress may increase the cell wall polysaccharide and lignin contents, while the starch content and the size of mesophyll cells may decrease [17]. There is an urgent need to understand how genes (genomics), proteins (proteomics), ions (ionomics), metabolites (metabolomics), transcripts (transcriptomics), and phenotypes (phenomics) are related to the stress of concern so that heat-stress-tolerant crop varieties can be developed [129]. Materials like melatonin, which can promote the photosynthetic process, improve enzyme activities, and increase the production of ATP, can support heat-stressed plants [159]. The harmful effects of heat stress on plants can also be alleviated by applying certain elements (e.g., Ca, Se, and Si), materials, and plant-growth-promoting rhizobacteria (PGPR) [160,161]. An overview of materials that may be used is given in Table 1. Biochar, β -sitosterol, seaweed extract, chitosan, sodium nitroprusside and gibberellic acid, brassinosteroids, abscisic acid, nano-chitosan–glycine betaine, nitric oxide, and various Si and Se materials can be useful [109,162–166].

Table 1. Response of cultivated plants under heat stress to anti-stressors.

Plant Species	Anti-Heat-Stressor	Impact	Ref.
Common thyme (<i>Thymus vulgaris</i> L.)	Eucalyptus wood-derived biochar (5%) and β -sitosterol (100 ppm)	Enhanced tolerance by increasing photosynthetic pigment production and antioxidant activity, and by maintaining the nutrient supply.	[120]
Rice (<i>Oryza sativa</i> L.)	Biochar application (40 g kg ⁻¹ soil)	Increased rice tolerance by improving the root-zone environment.	[164]
<i>Brassica juncea</i> (L.) Czern & Coss	Ortho-silicic acid (3 ppm); seaweed extract (5 ppm)	Both treatments mitigated the adverse effects of heat stress by increasing the photosynthetic rate and chlorophyll content and decreasing membrane injury and the MDA content.	[167]
Rice (<i>Oryza sativa</i> L.)	Silicon (12 g per pot)	Increased yield, dry matter accumulation, and tolerance under high-temperature conditions.	[168]
Table grapes (<i>Vitis vinifera</i> L.)	Silica fertilizer (23% Si)	Increased yield and quality, mainly by increasing total soluble solids, macro- and micro-nutrients, and photosynthesis efficiency.	[169]
Wheat (<i>Triticum aestivum</i> L.)	Selenium at 25, 50, 75 and 100 mg Se L ⁻¹	Under heat stress, 75 mg Se L ⁻¹ provided more of a benefit than the other doses.	[170]
Wheat (<i>Triticum aestivum</i> L.)	Nano-chitosan–glycine betaine 100 mM for 18 h	Seed priming improved heat and drought tolerance by osmotic adjustment, conserving water, activating antioxidants, and increasing yield.	[171]
Cotton (<i>Gossypium hirsutum</i> L.)	Foliar chitosan (0.2, 0.4, 0.6, and 0.8 g L ⁻¹)	Under heat stress, 0.8 g L ⁻¹ increased fiber quality and phenological and yield attributes more than the other doses.	[172]
Wheat (<i>Triticum aestivum</i> L.)	Sodium nitroprusside and gibberellic acid (100 μ M and 5 μ g/mL)	The treatment increased NO, H ₂ O ₂ , SOD, POD, APX, proline, GR, and GB that scavenged ROS and decreased the adverse effects of stress.	[173]
Soybean (<i>Glycine max</i> L.)	Brassinosteroids as 24-epibrassinolide (up to 1 μ M)	Improved the capacity of antioxidants to protect the photosynthetic apparatus under heat stress.	[166]

Table 1. Cont.

Plant Species	Anti-Heat-Stressor	Impact	Ref.
Wheat (<i>Triticum aestivum</i> L.)	Nitric oxide (100 μ M) and abscisic acid (100 μ M)	Regulated the expression and activity of enzymatic antioxidants, with produced osmolytes acting as a possible strategy for heat tolerance.	[165]
<i>Chrysanthemum morifolium</i> Ramat.	Biological nano-Se (50, 100, 150 and 200 mg L ⁻¹)	Nano-Se to 200 L ⁻¹ improved heat tolerance by enhancing antioxidant enzymes and decreasing polyphenol oxidase and electrolyte leakage.	[174]
Wheat (<i>Triticum aestivum</i> L.)	Biological Se-NPs (100 mg L ⁻¹)	Enhanced plant tolerance to drought and heat stress by increasing growth and productivity; inhibited fungal disease as well.	[175]
Cucumber (<i>Cucumis sativus</i> L.)	Silicon (200 mg L ⁻¹) and nano-Se (25 mg L ⁻¹)	Both Se and Si foliar applications boosted plant growth and the yield of cucumber under salinity and heat stress by increasing fruit yield and quality.	[176]

Abbreviations: MDA (malondialdehyde), SOD (superoxide dismutase), POD (peroxidase), APX (ascorbate peroxidase), GR (glutathione reductase), GB (glycine betaine), ROS (reactive oxygen species).

4. Nano-Food Farming: Is It a Crucial Solution?

Agriculture is the main source of our food [126]. Adapting agriculture to climate change is a critical approach to sustain food security and avoid deteriorating major natural resources, including soil and water. These adaptations might involve agronomic management (e.g., reducing soil water evaporation, altered cultivation schedules, and irrigation expansion), genetic improvements (through the cultivation of tolerant cultivars), and application of amendments such as nanomaterials. How can the nano-food farming approach support plant and animal production under different stresses such as heat stress? Is nano-food farming a reasonable solution to address heat stress? To what extent can this solution support global food security? Which sectors in agriculture can utilize the nano-food farming approach to address heat stress? Several questions need to be answered to determine whether the nano-food farming approach is a solution to heat stress. Many studies have investigated the potential of nanotechnology as a potent and novel technique to enhance the agricultural food sector (e.g., [34,177,178]). Nano-farming for food security can be achieved with farming practices such as applying suitable nano-agrochemicals to improve crop performance [96,179–182], nano-bioremediation of polluted soil and water [183], and nano-smart farming for food security [44,184]. Heat stress can shorten crop growing cycles and phenology, which reduces the total biomass and productivity [185]. Furthermore, warmer temperatures intensify evapotranspiration, leading to water stress and limited yields [105]. More studies are needed to investigate this approach, as presented in the following sections.

5. Nano-Farming for Global Food Security

What is the relationship between the nano-farming system and food security? What are the obstacles to achieve global food security? To what extent can the nano-farming system contribute to food security?

Nano-farming has both direct and indirect relationships with global food security, depending on which farming practices are used. For example, there are many agricultural practices linked directly to food production, such as nano-fertilization, nanopesticides, etc. Recently, many reports have confirmed that nanotechnology can contribute to global food security amid the escalating challenges posed by the growth of the global population and the impacts of climate change [43,182,186–188]. The use of nanomaterials in producing food has received substantial investigation, such as nano-identification and tracking of agri-foods [189], nano-management of agro-wastes [190,191], nano-biosensors to detect pathogens [192], nano-enhancement of the shelf-life of agri-products [193], nano-agrochemicals for crop improvement [179], nanofibers for wastewater treatment [194], nano-bio-remediation of soil and water [195], and nano-carriers to provide targeted delivery of treatments [196]. These areas of nanomaterials research help address the overarching

issue of global food security. This review aims to shed light on the transformative potential of nanotechnology to pave the way for a more resilient and sustainable future for agriculture.

Nano-farming approaches may include nano-priming of seeds [171,197]. Al Masruri et al. [171] primed wheat seeds with chitosan–glycine–betaine s (100 mM) for 18 h and found that the nano-priming improved heat tolerance. They linked the improvements to an adjusted osmotic pressure that conserved the tissue water content, activated the antioxidant system, supported carbon assimilation, and activated grain-filling enzymes, all processes that sustain crop productivity. Nano-fertilization and nano-plant protection are other potential practices. Nano-selenium has shown positive results against heat stress [174,176], as has nano-silicon [198]. Sári et al. [40] found that a biological form of the nanomaterials is preferable over other forms. Nanotoxicity and nano-safety are urgent issues that may lead to food insecurity under the nano-farming system if nanomaterials are mismanaged.

6. Nano-Management of Heat Stress

Which nanomaterials are effective against heat stress in plants or animals? What are the necessary doses of NMs needed under which temperatures to alleviate heat stress?

Many management practices may be used to prevent heat stress in plants. These include traditional methods such as temporary shading to protect crops from excessive sun exposure during heat waves, sufficient watering, particularly spraying, applying mulch to reduce soil temperatures and conserve water, and using heat-resistant crop cultivars [18]. Agrivoltaics, the production of crops and/or livestock beneath solar panels, has also shown promise to reduce the impacts of heat stress on crops and animals due to the shading effect of the solar panels and modification of the microclimate under the panels [199–201]. Approaches to mitigate heat stress can be grouped into (1) agronomic management, (2) genetic improvement, and (3) nano-farming (Figure 9; [17,30,141,162]). Plants can prepare for heat stress by thermo-priming or by protecting themselves from as much damage as possible by thermotolerance. Agronomic strategies include crop factors (earlier planting dates, analyzing crop growth responses, and changing the crop type or growing cycles), soil factors (reducing soil evaporation by mulching, soil conservation with amendments, and changing the fertilizer system), and water factors (hanging irrigation systems, reducing water and energy consumption, and improving crop water use and water productivity) [105].

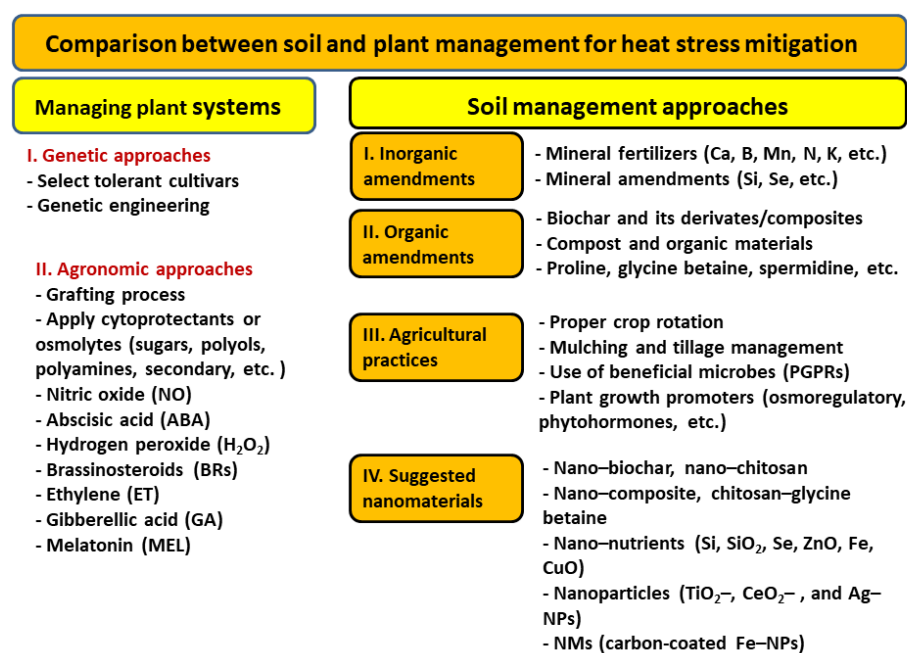


Figure 9. Comparisons between soil and plant management approaches for heat stress mitigation [141,162].

Nanomaterials such as nano-Se, nano-ZnO, nano-chitosan, and nano-TiO₂ can also enhance crop production under heat stress (Table 2). The main impact of heat stress on crops may be in creating oxidative stress and the generation of ROS, reducing photosynthesis and vegetative and reproductive phases [17,140,162,202–204]. Reviews on crop heat stress include molecular and agronomic attributes in crops like wheat [205], maize [204], rice [206], tomato [140], and peas [207], or on plants in general [29,109,202,208]. As presented in Table 2, each applied NM had a certain action against heat stress at a given dose under the studied conditions. Plants can be protected against heat stress by enhancing the antioxidant defense system and mitigating physio-biochemical and gene expression attributes [209–211]. Under heat stress, NMs offer many advantages for targeted slow release and transportation compared with organic molecules [212]. Applied NMs can support stressed plants to reduce the negative effects of heat stress and improve their tolerance to high temperatures [213]. These NMs can also regulate and activate specific stress-related genes, which in turn increase heat shock protein activity and aquaporin to enable plants' resistance to such stress [212]. The application of NMs also enhances the plant survival under such stress conditions by supporting the adaptations of the plant anatomy and regulating the opening of plant stomata under heat stress [214].

Table 2. Impact of nanomaterials (NMs) on cultivated plants under heat stress.

Plant Species	Applied NMs	Heat Stress	General Impact	Ref.
Wheat (<i>Triticum aestivum</i> L.)	Se-NPs foliar spray (10 mg·L ⁻¹)	38 °C for 5 h·day ⁻¹	NMs mitigated physio-biochemical and gene expression attributes under heat stress.	[209]
Bread wheat (<i>Triticum aestivum</i> L.)	Nano-sized chitosan–glycine betaine (100 mM)	37/28 °C all seasons (4 months)	NMs increased the activity of antioxidant enzymes and sustained plant growth and yield.	[171]
Mung bean (<i>Vigna radiata</i> L.)	Nano-ZnO (15, 30, 45, and 60 mg L ⁻¹)	40 °C during the flowering stage	Foliar nano-ZnO protected plants from heat stress by improving physiological and biochemical attributes.	[149]
Cucumber (<i>Cucumis sativus</i> L.)	Bio-nano-Se at 25 mg L ⁻¹	41 to 26 °C all season	Foliar NPs-Se promoted plant growth by increasing nutrient uptake and plant biomass.	[176]
Sorghum (<i>Sorghum bicolor</i> L. Moench)	Foliar applied Se-NPs (10 ppm)	38 °C for 10 days	Se-NPs can protect sorghum plants by enhancing the antioxidative defense system under heat stress.	[210]
Wheat (<i>Triticum aestivum</i> L.)	Foliar nano-Se (5, 10, 50 mg L ⁻¹)	Not mentioned	Gene expression of heat shock factor (A4A) and high-molecular-weight glutenin subunit 1Bx was altered; nitrate reductase activity was changed.	[211]
Tomato (<i>Lycopersicon esculentum</i> Mill.)	Nano-TiO ₂ (0.1–0.2 g L ⁻¹)	35 °C for 7 days	Nano-TiO ₂ promoted photosynthesis in tomato leaves under mild heat stress.	[215]

7. Nano-Food Farming and Nanotoxicity

Are there any negative sides of nano-farming? There is the potential for the accumulation of NMs in the environment that may pose serious risks to human health [216]. The main reasons for these risks (nanotoxicity) relate to the high chemical reactivity of NPs, greater access to human bodies, and bioavailability compared with larger particles. Environmental nanotoxicity still remains poorly understood and many questions need to be answered, such as what levels of nano-exposure are we currently facing? What levels of exposure could harm our health? What are the main sources of nanotoxicity under the nano-farming approach? In general, all nano-farming practices can be considered a source of nanotoxicity if NMs are over applied. It is crucial that we be judicial in the use of NMs in farming practices to avoid problems from nanotoxicity [217]. Recent studies on the risks posed by nanotoxicity include nanotoxicity in agri-foods [178,217,218], nano-food packaging [219], nano-agrochemical applications [220,221], disruption of soil ecosystems [222], deterioration of human/animal health [223,224], and phytotoxicity [225,226].

Engineered nanomaterials have several benefits for crop growth and/or human health when they are applied in the right dose and form, with particular benefits shown for biological NMs. However, NMs can be toxic under overdose situations (Figure 10; [104,217,224,225,227]). Studies on the toxic mechanisms of NPs on human health have shown NPs can cause damages such as genotoxicity, oxidative stress, inflammation, and cytotoxicity in different cell types [224]. Oxidative stress results from NPs through ROS generation, DNA damage, mitochondrial dysfunction, and others [228]. Nanotoxicity in plants can cause damages, including morphological, physiological, biochemical, anatomical, and genetic damage. This toxicity may also include cytotoxicity via the disruption of the cell cycle and genotoxicity through boosting and triggering the genes and antioxidant enzymes controlling NP stress [225]. Nanotoxic stress can generate more ROS, leading to protein degradation, lipid peroxidation, DNA damage, mitochondrial deterioration, and malfunctioning of biomolecules [225]. Many future areas of research are needed, including the roles of plant metabolites and rhizosphere exudates on NM transformation in soil. The role of soil microorganisms at plant interfaces still needs to be explored, along with the kinetics of NM transformations in both soil and plants. Indeed, long-term studies of NMs in agro-ecosystems with a focus on soil quality are crucial [181]. The use of manufactured NMs in edible coatings and food packaging will undoubtedly increase the ingestion of NMs by humans. Although many NMs have been utilized as anti-microbials in nanofood packaging and as nano-sensor technologies, new health risks are possible due to the migration of NMs into foods from the packaging. Many nano-techniques can be used in food packaging, such as NPs (e.g., NP-TiO₂, -SiO₂, -Ag, and -ZnO), composites of nano-clay, nano-encapsulation, bio-nanocomposites, nano-emulsions, and nano-sensors [229]. Nanoagrochemicals, including nanofertilizers and nanopesticides, may cause health risks, as reported by many studies [179,227,230,231].

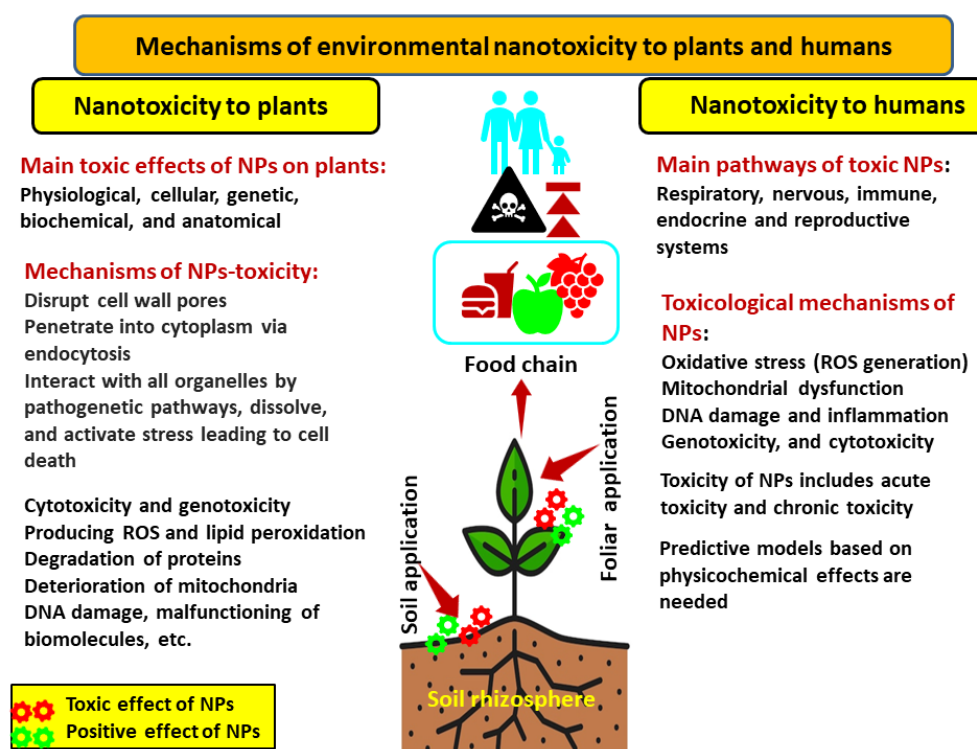


Figure 10. Mechanisms of nanotoxicity for both plants and humans. Nanotoxicity starts with the application of nanomaterials on soil and plants, which introduces NPs to the food chain and then to humans [104,217,224,225,227] (free image from https://www.freepik.com/premium-vector/plant-soil-growth-agriculture-color-line-icon_40823886.htm, accessed on 10 February 2024).

8. Conclusions and Future Perspectives

Climate change is a global threat facing us all. It includes overall increases in atmospheric temperature and the carbon dioxide content, and changes in precipitation amounts, timing, and patterns. These changes result in many extreme weather events that represent great challenges facing the management of natural resources such as water, energy, and soil, leading to challenges in food production. Heat stress can happen when the temperature exceeds 35 °C over time and is challenging to biological systems. Food security concerns due to heat stress are expected to increase under climate change, and several countries already suffer from food insecurity. Reductions in the production of crops, fish, and farm animals have been reported due to heat stress. The main impact of heat stress on cultivated plants involves the generation ROS and oxidative stress. Strategies including agronomic, molecular, and nano-approaches are needed to address heat stress in the future. Nano-management is a vital approach to fight stress that results from high temperatures, particularly biological nanomaterials. The concept of nano-farming for food security is a crucial strategy that requires more attention. This is needed at the farm level, as well as for researchers and decision makers.

This review identifies many questions concerning nano-farming, its features, problems, and challenges. Nanotechnology has important contributions to make to agro-business and global farming systems, but the overuse of nanomaterials may create nanotoxicity issues. It is important to determine management practices and NM application rates that can support nanofood farming and mitigate stresses such as heat stress on one hand, while avoiding nanotoxicity and its associated problems on the other hand. Many nanomaterials can now be found in commercial use, which may pose serious ecological risks. The production of adequate amounts of safe and healthy food for humanity has become a great challenge. This requires more efforts at all levels, including the national (for each country) and global levels. Addressing climate change and heat stress with nano-farming still needs research into the right management and regulations at the global level.

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