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A Study on the Impact of Climate Change on Field Crops Using Bio-Stimulants: Review Article

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Abstract: The stability of field crop production is increasingly being undermined by a changing climate. Rising mean and extreme temperatures, irregular rainfall, more frequent droughts, expanding soil salinity and increasing atmospheric carbon dioxide are acting together on cereals, legumes, oilseeds and vegetable crops, and the resulting losses in yield and quality are being felt through food prices and food security. Plant biostimulants, a group of products valued for what they do to the plant rather than for the nutrients they carry, have been put forward as an inexpensive input that may be built into climate-smart cropping systems. In this review, published evidence on how field crops respond to a warmer, drier and saltier environment, to elevated CO_2 and to combinations of these factors was first brought together. Products derived from algae and other plants, humic materials, hydrolysed proteins, useful bacteria and fungi, silicon, chitosan, nano-formulations and signalling molecules were then considered in turn, and the routes by which each of them limits injury at the cell and whole-plant level were traced. It was found that biostimulants act mainly through osmotic adjustment, reinforcement of antioxidant defence, hormonal regulation, improved root growth and nutrient acquisition, and the priming of stress-responsive genes. Positive responses have been reported widely, yet they are strongly dependent on product composition, crop, timing of application and environment, and most mechanistic knowledge has been obtained under controlled conditions. Multi-location field trials designed with sound statistical procedures, standardised product characterisation and the inclusion of quality and economic indicators are therefore recommended before biostimulants can be relied upon as a dependable adaptation measure for field crops.

Key words: Climate change; field crops; plant biostimulants; abiotic stress; drought; heat stress; salinity; sustainable agriculture

1. Introduction

Agriculture has been described as the sector most directly exposed to climate change, because crop growth is governed by temperature, water and atmospheric composition, all of which are now changing at an unprecedented rate. Global surface warming has averaged roughly 0.06 °C per decade over the period that began in 1850, yet after 1982 this pace has more than tripled, reaching close to 0.20 °C in every ten years **(Yuan *et al.*, 2024)**. According to the sixth IPCC synthesis, additional warming can no longer be avoided over the next few decades, and most parts of the world should expect hot extremes, intense rainfall and droughts affecting agriculture to occur more often **(IPCC, 2023)**. Global mean temperature has been predicted to rise by about 2 °C by 2100, and although higher CO_2 can stimulate photosynthesis, this benefit is largely offset by higher respiration, greater evapotranspiration, shorter crop duration and heavier pest pressure **(Malhi *et al.*, 2021)**. Semi-arid regions are particularly exposed; in the Mediterranean basin, reduced rainfall and widespread warming have already lowered freshwater availability while water demand continues to rise **(Noto *et al.*, 2023)**. Meanwhile, more people need to be fed every year. Cereal output would have to rise by roughly 70% if the world population passes the nine-billion mark by mid-century **(Neupane *et al.*, 2022)**, and past rates of yield gain do not appear sufficient for global production to double within that period **(Ray *et al.*, 2013; Godfray *et al.*, 2010)**.

This shortfall is not only an agronomic matter. A systematic review of crop price determinants showed that climate change may affect about 55% of the specific factors that shape crop prices, and that the general trend is towards higher prices as yields decline **(Nguyen *et al.*, 2024)**. Less food on the market and higher prices together put household food security at risk **(Rani & Reddy, 2023)**. Comparable conclusions have been drawn in places that differ greatly from one another: Pakistani farms growing rice in rotation with wheat **(Habib-ur-Rahman *et al.*, 2022)**, smallholder maize, sorghum and millet fields in West Africa **(Carr *et al.*, 2022)**, and the cool, short growing seasons of Newfoundland and Labrador **(Reza & Sabau, 2022)**. For India, a warming of 3 to 4 °C before 2100 has been linked with a 3 to 26% loss in net farm revenue, and farm incomes could fall by 12 to 40% in the absence of adaptation **(Kumari *et al.*, 2020)**. Indonesian work combining weather generators, catchment models and rice growth simulations has indicated that national rice self-sufficiency is put at risk by changing rainfall, hot spells and the movement of pests into new areas **(Ansari *et al.*, 2023)**.

Farming, however, is not only a victim. Close to 13.5% of human-made greenhouse gases are released by the agricultural sector, which is also responsible for about one half of all methane and three fifths of all nitrous oxide; manure and fertiliser, livestock digestion, flooded rice and the burning of biomass are the principal sources **(Zuma *et al.*, 2023)**. The open burning of crop residues alone has been reported to release large quantities of CO_2, CO, methane and particulate matter; Indian estimates indicate that nearly a quarter of the annual stubble output, about 84 out of 352 Mt, is set on fire after harvest **(Abdurrahman *et al.*, 2020)**. Adaptation measures that also reduce the reliance on synthetic inputs are therefore of double value.

Among the options proposed, plant bio-stimulants have attracted considerable attention. These products, which include extracts of seaweeds and other plants, humic substances, protein hydrolysates, beneficial bacteria and fungi, and certain inorganic compounds such as silicon, are applied in small amounts and are intended to improve plant performance under stress rather than to supply nutrients **(du Jardin, 2015**; **Yakhin *et al.*, 2017)**. Several reviews have argued that they could form part of a climate adaptation strategy for crops **(Van Oosten *et al.*, 2017**; **Bhupenchandra *et al.*, 2022**; **Bibi & Rahman, 2023)**. However, the literature on climate impacts and the literature on biostimulants have largely developed in parallel, and the evidence has rarely been examined from the standpoint of field crops grown under realistic climatic stress.

The aim of this review was therefore to bring these two bodies of evidence together. Four tasks were set: (i) to outline how a changing climate alters crop development, productivity and produce value; (ii) to describe how biostimulants are classified, legally defined and thought to work; (iii) to weigh the evidence of stress relief for each product group; and (iv) to point out where knowledge is still weak and how future field work could be organised.

2. Approach of the review

A narrative review approach was adopted. Peer-reviewed review articles, systematic reviews, meta-analyses and original experimental papers dealing with climate change effects on crops and with the use of biostimulants under abiotic stress were collected, with priority given to work published between 2010 and 2025. Earlier key studies were retained where they provided the conceptual or physiological basis of later research. The material was organised around two questions: how climate change is affecting field crops, and to what extent biostimulants can reduce these effects. Studies on vegetable and fruit crops were included where comparable field crop data were lacking, but their relevance to field crops was considered critically. Quantitative values were reported as given in the original sources, and no new statistical synthesis was attempted.

3. Climatic pressures on field crop production

3.1. Rising temperature and heat stress

Temperature is the climatic variable for which the clearest yield signal has been detected. When some thirty wheat simulation models were run side by side, a loss of close to 6% of world wheat output was obtained for every additional degree, assuming that farmers made no adjustment **(Asseng *et al*., 2015)**; the same modelling community later estimated what the 1.5 °C and 2 °C targets of the Paris Agreement would mean for wheat **(Liu *et al*., 2019)**. The comparison of experimental, process-based and statistical methods for estimating climate impacts has shown that, although the size of the effect differs among methods, the negative direction of warming effects on major cereals is consistent **(Feng *et al*., 2023)**.

The damage is most severe when high temperature coincides with sensitive developmental stages. In rice, flowering and early grain filling are particularly vulnerable, and spikelet sterility increases sharply above critical temperature thresholds **(Jagadish *et al*., 2015)**. Wheat exposed simultaneously to high temperature and water shortage after anthesis sets fewer and lighter kernels, and the balance between starch and protein laid down in the endosperm is also changed **(Zahra *et al*., 2021)**. In maize, post-flowering heat and drought were reported to impair physiology, yield and grain quality **(Bheemanahalli *et al*., 2022)**. Inside the cell, excessive heat makes membranes leaky, causes proteins to unfold and allows oxygen radicals to build up; whether a plant survives depends largely on molecular chaperones and on the gene networks switched on by heat-responsive transcription factors **(Bita & Gerats, 2013**; **Ohama *et al*., 2017**; **Ul Haq *et al*., 2019)**. Increased transpirational cooling, epicuticular wax deposition, altered membrane lipid composition and the accumulation of osmolytes and antioxidants have been described as adaptive responses **(Kumari *et al*., 2022)**.

Roots have received less attention than shoots, even though soil temperature is also rising. In warm soil, roots elongate less, branch differently and take up less water and fewer ions, so that the shoot is starved and yield falls **(Calleja-Cabrera *et al*., 2020)**. Root traits are therefore regarded as an important target for adaptation, both through breeding and through management practices that support root development. The main root responses to warming, alone and in combination with drought, salinity and nutrient deficiency, are summarized in Figure 1.

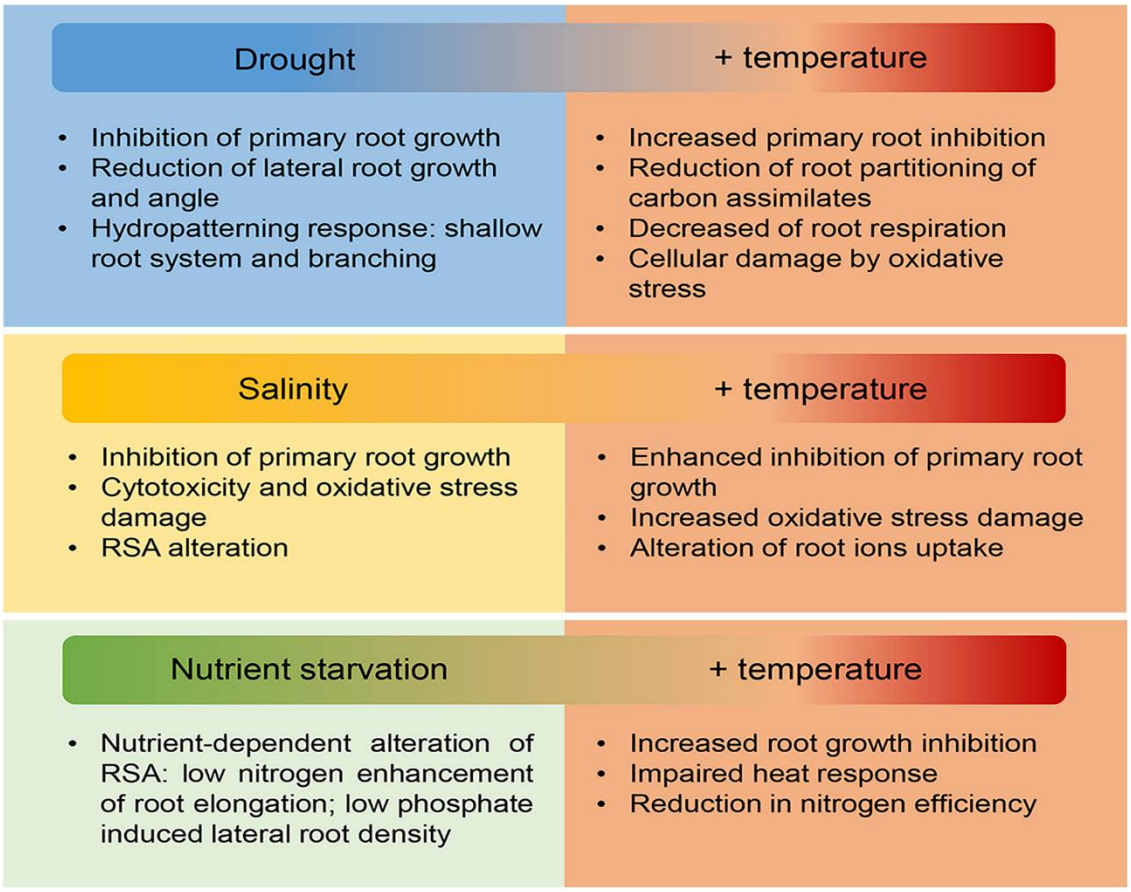


Figure 1. How root systems respond when warming is added to water shortage, salt or poor nutrition (RSA, root system architecture). ***Source: Calleja-Cabrera et al. (2020), Frontiers in Plant Science, reused under a CC BY 4.0 licence.***

At the regional level, the magnitude of expected losses is considerable. Pakistani day-time maxima are expected to climb by 2.8 °C between 2040 and 2069; under such conditions, DSSAT simulated rice and wheat harvests 15.2 and 14.1% lower than at present, whereas APSIM returned losses of 17.2 and 12%, respectively **(Habib-ur-Rahman *et al.*, 2022)**. Historical field data point in the same direction. Catalan variety trials conducted from 2007 to 2021 recorded a warming of half a degree per decade, and wheat headed earlier and produced grain of lower hectolitre weight as yearly mean and night-time temperatures rose; genetic yield progress was stagnant in spring wheat and showed signs of a plateau in winter wheat despite a linear gain of 1.31% per year **(Gulino *et al.*, 2023)**. In West Africa, the median yield decline of staple crops across scenarios was estimated at 6% **(Carr *et al.*, 2022)**.

3.2. Drought and altered rainfall

Water deficit remains the main cause of yield loss in rainfed agriculture. Projections for this century indicate that prolonged dry spells will become more common and more intense across roughly a third of the continents, while the gap between water demand and supply widens considerably **(Neupane *et al.*, 2022)**. The historical record from the United States has demonstrated how strongly drought controls the variability of maize and soybean production **(Zipper *et al.*, 2016)**. Drought reduces stomatal conductance and photosynthesis, disturbs nutrient uptake and translocation, and increases oxidative damage **(Fahad *et al.*, 2017)**. When it is combined with high temperature, the effects are usually more than additive. Maize hybrids subjected to both stresses together suffered greater losses in growth, mineral uptake, redox balance and grain yield than those exposed to only one of them **(Hussain *et al.*, 2019)**.

Excess water is also becoming more frequent. Changes in the timing and intensity of rainfall have been reported to shorten or lengthen growing seasons, delay sowing and favour waterlogging, soil erosion and the spread of pests and diseases **(Yuan *et al.*, 2024)**. For the Mediterranean basin, a reduction in surface runoff and groundwater recharge has been documented, and water scarcity has been identified as the most relevant consequence of climate change for agriculture in its southern regions, although projections carry considerable uncertainty from each step of the modelling chain **(Noto *et al.*, 2023)**.

3.3. Pests and diseases

Climate change also acts on crops indirectly through pests, pathogens and weeds. An expert panel convened by the IPPC Secretariat came to the view that a warmer world will change how easily pests infect crops, how much harm they do and where they occur, and that land climatically suited to invaders such as fall armyworm (*Spodoptera frugiperda*) is likely to grow **(IPPC Secretariat, 2021)**. Insects that survive mild winters can complete extra life cycles and become active sooner, while shifts in weed flora and higher pest infestation have been listed among the main indirect impacts on crop productivity **(Malhi *et al.*, 2021)**. Since many biostimulants are also claimed to enhance plant defence, this interaction between abiotic and biotic stress is relevant to their evaluation.

3.4. Soil salinity

Salinity is expected to extend under climate change through sea-level rise, higher evaporation, reduced leaching rainfall and greater dependence on poor-quality irrigation water. Two phases of salt injury are usually distinguished: an early osmotic phase, in which roots find it harder to extract water, and a later phase in which Na+ and Cl- reach toxic levels in leaves **(Isayenkov & Maathuis, 2019)**. Although many crops tolerate moderate salinity, yield of most glycophytic field crops declines once a threshold is exceeded **(Zörb *et al.*, 2019)**. The interaction of salinity with heat has been shown to produce a specific physiological and molecular response that cannot be predicted from either stress studied separately **(Rivero *et al.*, 2014)**. How costly this can be being shown by **Alae-Carew *et al.* (2020)**, who pooled experiments on fruits, nuts and seeds: irrigation water made saltier by 3 to 4 dS m^{-1} cut fruit yield by 28.2% on average, while halving the water supply cut it by 20.7%.

3.5. Elevated carbon dioxide and crop quality

More CO_2 in the air speeds up carbon fixation in C3 species and lets them lose less water per unit of dry matter; in the same synthesis, raising CO_2 by 75 to 100% was followed by an average fruit yield gain of 37.8% **(Alae-Carew *et al.*, 2020)**. This fertilisation effect, however, tends to be weakened when high temperature occurs at the same time **(Alae-Carew *et al.*, 2020)**, and C4 crops benefit less **(Kumari *et al.*, 2022)**. A more serious concern relates to quality. Grain grown at high CO_2 tends to contain 3 to 17% less protein, zinc and iron, and if 550 ppm is reached by 2050 this dilution alone could leave some 175 million more people short of zinc and 122 million more short of protein **(Leisner, 2020)**. Similar declines in mineral and protein content have been reported for vegetables **(Dong *et al.*, 2018)**. The systematic analysis of climate change literature on vegetable crops found that only 53 out of 219 publications dealt exclusively with these crops, and that quality and food safety had received far less attention than yield **(Dumitru *et al.*, 2023)**. Figure 2 places side by side the size of the yield responses quoted in this section.

3.6. Combined stresses and the need for integrated responses

A crop in the open rarely deals with one problem at a time. Hot, dry, saline and bright conditions tend to arrive together, and the plant answers such combinations with signalling and metabolic adjustments of its own rather than with the sum of the single-stress responses **(Rivero *et al.*, 2014**; **Hussain *et al.*, 2019)**. Two seasonal examples are sketched in Figure 3.

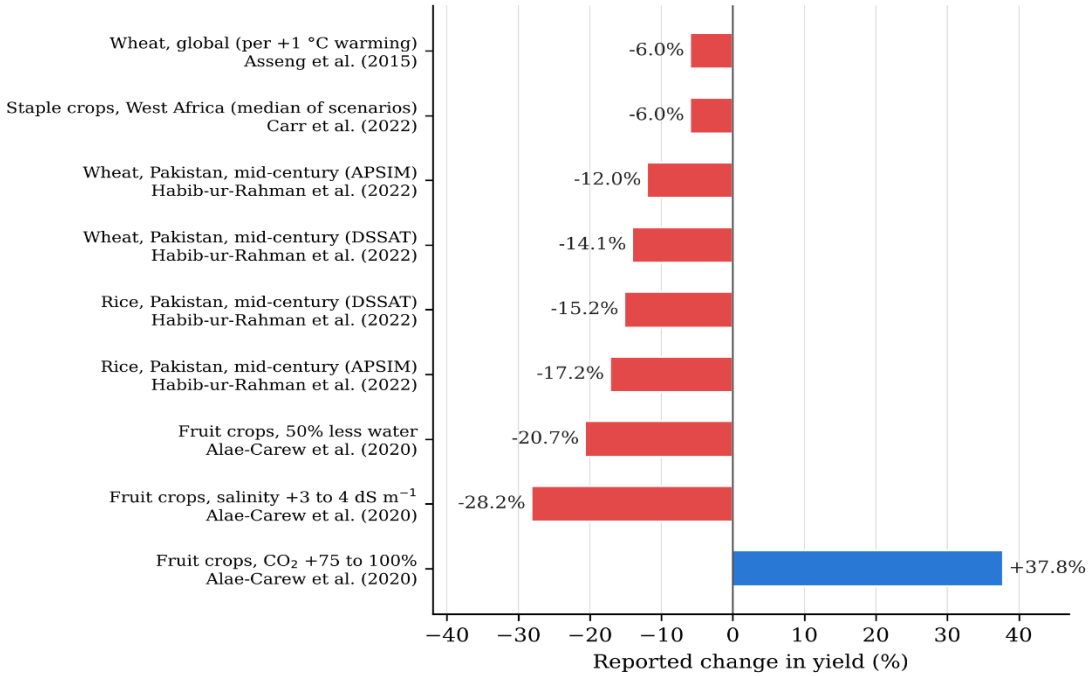


Figure 2. Yield responses to individual climatic factors as quoted in the studies cited in Section 3; bars to the left of zero are losses, and the single bar to the right shows the gain attributed to CO_2 enrichment. ***Source: drawn by the author from data reported by Asseng et al. (2015), Carr et al. (2022), Habib-ur-Rahman et al. (2022) and Alae-Carew et al. (2020).***

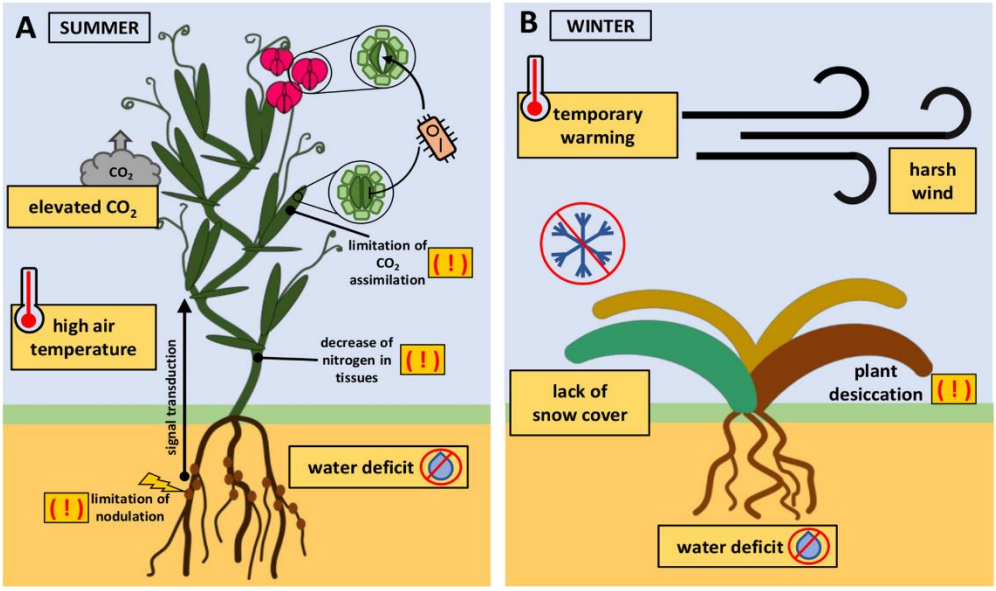


Figure 3. Two seasonal situations in which a crop meets several unfavourable factors at once: (A) a hot summer with more CO_2 in the air and a drying soil; (B) a mild, snowless winter with strong wind and little soil moisture. ***Source: Kopeć (2024), Plants, reused under a CC BY 4.0 licence. Oxidative stress is the common denominator. Whatever the stress, surplus oxygen radicals are generated in the organelles where electrons flow fastest, and the extent of injury depends mostly on how quickly SOD, CAT, APX and the Halliwell-Asada cycle can remove them (Gill & Tuteja, 2010). Any management tool intended to protect field crops under climate change must therefore act on several stress pathways simultaneously. This requirement is one of the main reasons why biostimulants, which typically contain mixtures of bioactive molecules, have been regarded as promising (Rouphael & Colla, 2018).***

Adaptation through management has already been shown to be effective. In West Africa, common adaptation practices such as optimised sowing dates and cultivars with longer cycles increased yields under climate change by about 13% compared with business-as-usual management **(Carr *et al.*, 2022)**. Tolerant cultivars, a wider use of hardy cereals such as millets, and improved husbandry have also been advocated **(Neupane *et al.*, 2022)**. The diversification of crop species and cultivars, supported by modern molecular breeding and field phenotyping, has been proposed as the basis of climate-resilient agriculture **(Kopeć, 2024)**, and water-smart, nutrient-smart, weather-smart and carbon-smart practices have been grouped under the climate-smart agriculture approach **(Malhi *et al.*, 2021)**. On the soil side, manuring, catch crops and ploughing straw back in rather than burning it are seen as ways of rebuilding humus and, with it, the capacity of the land to absorb shocks **(Abdurrahman *et al.*, 2020**; **Khan *et al.*, 2024)**. Biostimulants are best considered within this broader set of measures rather than as a stand-alone solution.

4. What a plant biostimulant is: definitions, groups and legal status

4.1. Definition

The term biostimulant has been used for more than two decades, but a widely accepted definition was only proposed relatively recently. In the definition offered by **(du Jardin , 2015)**, a biostimulant may be a substance or a living organism; what qualifies it is that it is given to the crop to make nutrition more efficient, to help the plant withstand abiotic stress or to raise produce quality, and its own mineral content is beside the point. The emphasis was thus placed on the agricultural function of the product rather than on its composition. A similar view was expressed by **(Yakhin *et al.*, 2017)**, who argued that biostimulants should be defined by the plant response they produce and that their action should be distinguished from that of fertilisers and plant protection products. An extensive overview of agricultural uses was provided by **(Calvo *et al.*, 2014)**, who described the main product groups and the range of crops and conditions in which they have been tested.

Bhupenchandra *et al.* (2022) drew a simple line between products that contain no living cells (chitosan, humic and fulvic fractions, hydrolysed proteins, phosphites, algal extracts and silicon) and those based on organisms (AMF, PGPR and Trichoderma); either kind may be sprayed on leaves, delivered through the irrigation water or placed in the soil. European law now treats biostimulants as a distinct class of fertilising product. Under Regulation 2019/1009, such a product must act on the plant's own nutritional processes, not by supplying nutrients, and its claimed purpose is limited to four outcomes: better use of nutrients, better resistance to abiotic stress, better quality, or release of nutrients that are otherwise locked in the soil **(European Union, 2019)**. For the purposes of this review, the important point is that a stress-tolerance claim is accepted by the regulation but has to be backed by evidence.

4.2. Main categories

du Jardin (2015) listed seven groups. Four are of non-living origin: humic-type substances, nitrogen-rich compounds such as hydrolysed proteins, extracts of algae and higher plants, and biopolymers led by chitosan. A fifth group covers beneficial mineral elements, silicon in particular, and the last two consist of useful fungi and bacteria. **Bibi and Rahman (2023)** followed much the same scheme but added vitamins, free amino acids, antioxidant preparations, metabolites recovered from microbial cultures, film-forming anti-transpirants and chitin-based materials. More recently, nanomaterials and nano-formulations have been proposed as carriers or as active ingredients **(Fincheira *et al.*, 2021; Zuma *et al.*, 2023)**, and microbial products have been grouped as microbial plant biostimulants **(Ali *et al.*, 2022)**.

A distinction is usually drawn between biostimulants and biofertilisers, although the boundary is not always sharp. A biofertiliser is expected to put more N, P or K within reach of the roots, by fixing atmospheric nitrogen or by releasing bound phosphate and potassium, whereas a biostimulant is judged by the way it changes the plant's own functioning **(Mehata *et al.*, 2023; Mącik *et al.*, 2020)**. In practice, many microbial inoculants perform both functions, and integrated bio-organic fertilisation has been shown to increase field crop yields while reducing chemical inputs **(Daniel *et al.*, 2022; Mawlood *et al.*, 2025)**. For the purpose of this review, microorganisms were considered when their effect on stress tolerance was reported.

5. Mechanisms through which biostimulants reduce climate-related stress

The modes of action of biostimulants have been reviewed extensively, and it is now accepted that most products act through several mechanisms at the same time **(Van Oosten *et al.*, 2017; Rouphael & Colla, 2018)**. An overview of these mechanisms, from the molecular level to the anatomical level, is presented in Figure 4, and the mechanisms most relevant to climatic stress are discussed below.

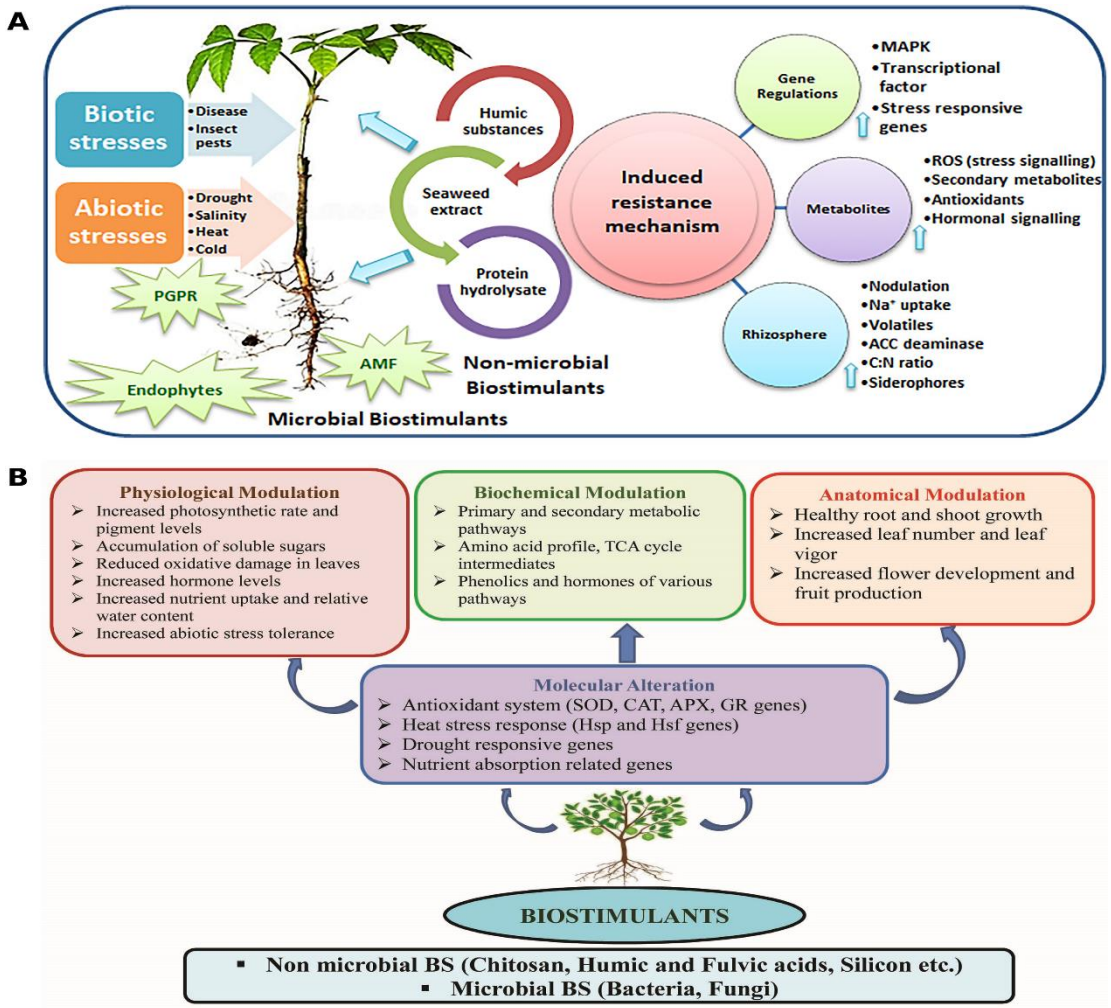


Figure 4. Ways in which biostimulants protect crops from biological and environmental injury: (A) living and non-living products and the resistance they induce; (B) changes they bring about at the gene, metabolic, physiological and structural levels. *Source: Bhupenchandra et al. (2022), Frontiers in Plant Science, reused under a CC BY 4.0 licence.*

5.1. Osmotic adjustment and water relations

A common effect of biostimulant treatment is a rise in the cell content of low-molecular osmolytes, among them proline, betaines and sugars, which helps tissues stay turgid when water is scarce or the soil solution is saline. Seaweed extracts, protein hydrolysates and some microbial inoculants have been associated with higher relative water content and delayed wilting under water deficit **(Bulgari *et al.*, 2019)**. Field-grown onion inoculated with Trichoderma album contained 34% more proline in its leaves and well over twice as much free amino acid as the control **(Bibi & Rahman, 2023)**. A product made from natural organic matter increased root growth by 36% and shoot growth by 27% in tomato under drought, and an Ascophyllum nodosum extract improved the drought resistance of tomato by 40% compared with the control **(Bibi & Rahman, 2023)**.

5.2. Reinforcement of antioxidant defence

Because oxidative damage is common to heat, drought and salinity, the stimulation of antioxidant enzymes is one of the most frequently reported effects. Onion plants receiving Trichoderma album or Bacillus megaterium showed stronger SOD, CAT, APX and GST activity and were richer in vitamin C and flavonoids **(Bibi & Rahman, 2023)**. Plant-based and microbial products have been reported to protect photosynthesis by increasing antioxidant capacity and upregulating stress tolerance genes **(Ali *et al*., 2022; Zuma *et al*., 2023)**. This mechanism directly addresses the reactive oxygen species burden described by **(Gill and Tuteja, 2010)**.

5.3. Hormonal regulation and signalling

Several biostimulants contain or induce plant hormones, or interact with hormone signalling. Seaweed extracts contain cytokinins, auxins and betaines, and their effects are partly attributed to these compounds **(El Boukhari *et al*., 2020)**. Salicylate, for instance, adjusts the redox machinery, carbon assimilation and solute build-up, and through these the plant's response to hot, dry or saline conditions **(Khan *et al*., 2015)**. Rice sprayed with salicylate together with a low dose of H2O2 coped better with water shortage **(Sohag *et al*., 2020)**; in wheat, NO and ABA acted together to keep photosynthesis running at high temperature by controlling osmolyte and antioxidant levels **(Iqbal *et al*., 2022)**; and soaking wheat grains in L-arginine before sowing produced more vigorous plants under drought **(Hussein *et al*., 2022)**. Although such signalling compounds are not always classified as biostimulants, they illustrate the type of physiological reprogramming that many commercial biostimulants aim to induce.

5.4. Root growth and nutrient acquisition

Root architecture is sensitive to soil warming and drying **(Calleja-Cabrera *et al*., 2020)**, and a larger, more active root system is one of the effects seen most reliably after treatment with humic materials, hydrolysed proteins or root-associated microbes. Biofertilisers and plant growth-promoting rhizobacteria enlarge the volume of soil explored by roots, solubilise phosphorus and fix nitrogen, which helps to maintain nutrition when water uptake is restricted **(Mehata *et al*., 2023; Mawlood *et al*., 2025)**. Arbuscular mycorrhizal fungi extend the absorbing surface through their hyphae and have been reported to improve water and nutrient acquisition under drought. In onion, potassium concentration increased by 105.7% and calcium by 37% following microbial biostimulant application **(Bibi & Rahman, 2023)**.

5.5. Priming and gene expression

An important concept is priming, by which a plant exposed to a biostimulant responds more quickly and more strongly to a subsequent stress. Treated plants switch on stress-related genes earlier or more strongly, although how much they do so varies with the crop, the way the product is applied and the plant's hormonal status **(Bibi & Rahman, 2023)**. Chaperone genes, regulatory proteins and genes coding for ROS-scavenging enzymes figure prominently among those affected **(Ul Haq *et al*., 2019; Ali *et al*., 2022)**. The practical advantage of priming is that tolerance can be enhanced without the yield penalty that is often associated with constitutive defence.

6. Evidence for stress mitigation by biostimulant category

6.1. Seaweed and other botanical extracts

No biostimulant is sold in larger volume than algal extracts, and products made from the North Atlantic kelp Ascophyllum nodosum dominate the market. Because what ends up in the bottle depends on the alga used and on how it is processed, two extracts can behave quite differently in the field **(El Boukhari *et al*., 2020)**. Under salinity, an A. nodosum extract provoked a positive phenotypic response in watermelon transplants, and in tomato it improved drought resistance markedly **(Bibi & Rahman, 2023)**. Extracts of the red alga Chondrus crispus conferred drought tolerance in tomato together with greater shoot height and biomass, while Yucca schidigera extracts improved germination, early vigour and tolerance of drought and salt stress in broccoli **(Bibi & Rahman, 2023)**. Evidence from field crops is also accumulating. A Gracilaria dura extract significantly increased wheat biomass and yield under drought by supporting water-saving mechanisms, and extracts of Kappaphycus alvarezii and Gracilaria edulis applied at 10 and 15% improved nitrogen and phosphorus uptake in rice **(Bhupenchandra *et al*.,**

2022). Sugarcane sprayed with a 5% solution of the red seaweed Kappaphycus alvarezii on top of the usual fertiliser was calculated to avoid around 260 kg of CO_2-equivalent emissions for every tonne of cane harvested from a hectare **(Bhupenchandra *et al.*, 2022; Bibi & Rahman, 2023)**. Such results suggest that the climate benefit of biostimulants may come both from adaptation and from mitigation.

6.2. Humic substances and organic matter-based products

Humic-type fractions encourage roots to grow and absorb ions, partly by activating the proton pumps of root cell membranes. In a three-year wheat study, a mixture of biostimulants increased soil humus content and the release of mobile humic substances and humic acids, together with soil nitrogen and carbon **(Bibi & Rahman, 2023)**. Composted and fermented organic materials and farmyard manure give the soil a better crumb, hold more water and feed a more varied microflora; applied in rotations that include cover crops, they are regarded by **(Khan *et al.*, 2024)** as a practical means of building soil carbon and soil quality in a changing climate. Because soil organic matter buffers both drought and temperature extremes, products that raise or protect it are expected to make crops less vulnerable to climatic variability.

6.3. Protein hydrolysates and amino acids

Hydrolysates obtained from vegetable or animal proteins deliver short peptides and single amino acids, which the plant can use as signals, as osmotic solutes or as building blocks for hormones. Better nitrogen assimilation, stronger roots and greater resistance to salt, water shortage and temperature extremes have been attributed to them, mostly in vegetables **(Bulgari *et al.*, 2019)**. Combining a microbial biostimulant with a plant-derived protein hydrolysate has been suggested as a way to achieve synergistic effects that a single product cannot provide **(Rouphael & Colla, 2018)**. Data from cereals and legumes grown in open fields are still limited for this category, and this gap deserves attention.

6.4. Microbial biostimulants

No other group is as varied as the one made up of useful microbes. Plant growth-promoting rhizobacteria can produce phytohormones, siderophores and exopolysaccharides, lower stress ethylene through ACC deaminase, and improve nutrient availability **(Ali *et al.*, 2022)**. Wheat inoculated with AKMP7, a heat-tolerant isolate of Pseudomonas putida, grew better at high temperature than uninoculated plants **(Ali *et al.*, 2011)**; this is still one of the more convincing cases of a bacterium protecting a cereal from heat. Field application of Trichoderma album and Bacillus megaterium increased the yield and quality of onion and enhanced its antioxidant system **(Bibi & Rahman, 2023)**. Microbial products have also been proposed as part of integrated nutrient management, where they can partly replace mineral fertilisers and thereby reduce emissions associated with fertiliser production and use **(Mahapatra *et al.*, 2022; Zuma *et al.*, 2023)**. Their weak point is unpredictability: an inoculant that works in one field may fail in the next, because whether it establishes and stays active is decided by the soil, by the resident microflora and by the weather **(Mącik *et al.*, 2020; Daniel *et al.*, 2022)**.

6.5. Silicon, chitosan and nanomaterials

Although most crops can complete their life cycle without silicon, plants supplied with it often withstand dry, saline or hot conditions better; silica deposited in the walls stiffens the tissues and cuts cuticular water loss, and the antioxidant system is also helped. A silicate compound combined with antagonistic Bacillus species improved the physiological growth of banana and reduced Fusarium wilt incidence by 56.25% **(Bibi & Rahman, 2023)**, showing that biostimulants may also help against biotic stresses whose distribution is shifting with climate. Chitosan, obtained by deacetylating the chitin of crustacean shells, serves both to trigger plant defences and to encapsulate other actives. When menadione sodium bisulfite was enclosed in chitosan nanoparticles, tomato plants withstood drought better and needed a second application seven days later than usual **(Bibi & Rahman, 2023)**. Particles of Fe, Si and Ti in the nanometre range stimulated growth and metabolism of wheat, maize, soybean and spinach **(Zuma *et al.*, 2023)**, and carriers of this size allow nutrients and active compounds to reach plant tissues with smaller losses **(Fincheira *et al.*, 2021)**. However, the long-term behaviour of

nanomaterials in soil and food chains has not yet been fully evaluated, and a cautious approach is warranted.

6.6. Overview of selected studies

Representative results reported for different biostimulants under climate-related stresses are summarised in Table 1. Vegetable crops dominate the list simply because most trials so far have been carried out on them, not because cereals and legumes are expected to respond less.

Table 1. Selected examples of biostimulant effects on crops exposed to climate-related stresses

Biostimulant	Crop	Stress or condition	Main reported effect	Source
Trichoderma album and Bacillus megaterium	Onion	Field conditions	Higher yield; K +105.7%, proline +34%, free amino acids +144%; higher antioxidant enzyme activity	Bibi & Rahman (2023)
Natural organic matter-based product	Tomato	Drought	Root growth +36%, shoot growth +27%	Bibi & Rahman (2023)
Ascophyllum nodosum extract	Tomato	Drought	Drought resistance increased by 40% relative to control	Bibi & Rahman (2023)
Ascophyllum nodosum extract	Watermelon	Salinity	Positive phenotypic response of transplants	Bibi & Rahman (2023)
Chitosan nanoparticles with menadione sodium bisulfite	Tomato	Drought	Higher tolerance; retreatment delayed by one week	Bibi & Rahman (2023)
Yucca schidigera extract	Broccoli	Drought and salinity	Better germination, early vigour and stress tolerance	Bibi & Rahman (2023)
Kappaphycus alvarezii extract (5% foliar)	Sugarcane	Field, recommended fertilizer	Estimated emission saving of about 260 kg CO2-eq per tonne of cane	Bhupenchandra *et al*. (2022)
Gracilaria dura extract	Wheat	Drought	More dry matter and more grain	Bhupenchandra *et al*. (2022)
Kappaphycus alvarezii and Gracilaria edulis extracts (10 and 15%)	Rice	Field, full fertiliser dose	Higher N and P uptake	Bhupenchandra *et al*. (2022)
Pseudomonas putida AKMP7	Wheat	High temperature	Better growth than uninoculated plants	Ali *et al*. (2011)
Salicylic acid with hydrogen peroxide	Rice	Drought	Attenuation of drought damage	Sohag *et al*. (2020)
L-arginine grain priming	Wheat	Drought	Improved growth performance	Hussein *et al*. (2022)
Mixture of microbial and organic biostimulants	Wheat	Three-year field study	Higher soil humus, N and C; release of mobile humic substances	Bibi & Rahman (2023)

7. Biostimulants within climate-smart cropping systems

The value of biostimulants for field crops is likely to be greatest when they are integrated with other adaptation and mitigation practices. **Rani and Reddy (2023)** argued for climate-smart farming, in which higher output, greater stability and fewer emissions are pursued together, and agro-ecological approaches have been recommended where climate change has aggravated existing food security problems **(Reza & Sabau, 2022)**. Organic agriculture, which relies on biological processes for nutrient supply and pest control, has been discussed both as a contributor to mitigation and as a source of

resilience **(Scialabba & Müller-Lindenlauf, 2010; Reganold & Wachter, 2016)**. A classification of adaptation strategies into short-, mid- and long-term measures, in which sustainable fertiliser solutions occupy a central position, is shown in Figure 5. Within such systems, biostimulants and biofertilisers can partially substitute for synthetic fertilisers, and it was noted that the European Commission has set the objective of replacing a share of chemical fertilisers with organic-based inputs **(Bibi & Rahman, 2023)**.

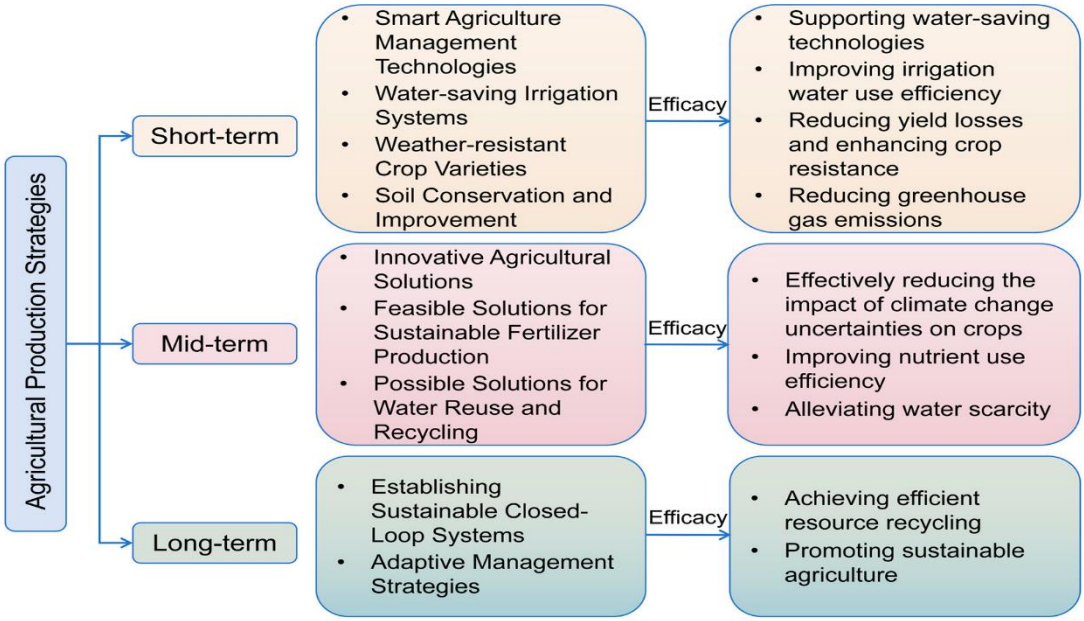


Figure 5. Adaptation options for farming grouped by time horizon (near, intermediate and distant) together with the benefit expected from each. ***Source: Yuan et al. (2024), Agronomy, reused under a CC BY 4.0 licence.***

Several practical combinations can be envisaged. Seed treatment or seedling inoculation with microbial biostimulants can be used to establish beneficial populations early, when crops are most exposed to irregular rainfall. Sprays of algal extract, hydrolysed protein or silicon could be given a few days ahead of a forecast hot spell, or just before anthesis and the start of kernel filling, when yield is most easily lost. Humic products and organic amendments worked into the soil would raise its capacity to store water and support microbial life, while the incorporation of residues, instead of burning, can supply the organic matter on which these processes depend **(Abdurrahman *et al*., 2020; Khan *et al*., 2024)**. Site-specific nutrient management and reduced chemical inputs have also been shown to support soil microbial processes and crop yields **(Zuma *et al*., 2023)**. Low-input management tools of this kind have been described as particularly suitable for sustainable vegetable and crop production **(Shahrajabian *et al*., 2021)**.

The mitigation side should not be overlooked. If biostimulants allow fertiliser rates to be reduced without yield loss, emissions of nitrous oxide and the energy cost of fertiliser manufacture are reduced as well **(Bibi & Rahman, 2023; Mahapatra *et al*., 2022)**. Such benefits are, however, rarely measured directly in biostimulant trials. In one of the few cases where they were calculated, combining an AMF inoculant (Glomus intraradices) with a vegetal hydrolysate lowered the carbon footprint of zucchini by 7 to 12% and of spinach by 7 to 24% **(Bhupenchandra *et al*., 2022)**. Organic fertilisers derived from manure, compost, digestate and biochar may increase emissions shortly after application, but they frequently lead to net carbon sequestration in soil and reduce the fossil energy used in synthetic fertiliser production, particularly in Mediterranean agroecosystems with low soil organic matter **(Badagliacca *et***

***al*., 2024)**. The inclusion of emission measurements in future experiments would therefore strengthen the case for these products.

8. Open questions and suggestions for further work

Encouraging as many of the published results are, they have to be read with some caution. First, the response to biostimulants is highly variable. **When Li *et al*. (2022)** pooled open-field experiments, yields were higher with biostimulants on average, but by very different amounts depending on what was applied, to which crop, and on what soil and in what climate. Second, much of the mechanistic knowledge has been obtained in pots, growth chambers or greenhouses, and it has been emphasised that understanding under field conditions remains limited **(Bibi & Rahman, 2023)**. Third, most products are complex and poorly characterised mixtures, so that results obtained with one product cannot be transferred to another, even within the same category **(El Boukhari *et al*., 2020; Rouphael & Colla, 2018)**. Fourth, the research effort is unevenly distributed. Climate impact studies are concentrated in industrialised countries, while the regions that are most vulnerable have been studied least **(Dumitru *et al*., 2023)**, and field crops have received less attention in biostimulant research than high-value horticultural crops **(Bulgari *et al*., 2019)**.

Methodological issues also deserve attention. The comparison of manipulated experiments, crop models and statistical models has shown that each method carries its own uncertainty, and that multi-method approaches give more reliable estimates of climate impact **(Feng *et al*., 2023)**. The same principle can be applied to biostimulant research: controlled experiments are needed to identify mechanisms, but conclusions on agronomic value require field trials repeated over locations and seasons. Such trials should be laid out in appropriate designs, such as randomised complete block or split-plot designs where biostimulant treatments are combined with irrigation or fertiliser levels, and analysed with suitable procedures for combined analysis over environments and for mean comparisons **(Gomez & Gomez, 1984)**. Untreated controls, and where possible controls receiving the same amount of nutrients as contained in the product, should be included so that a genuine biostimulant effect can be separated from a nutritional one, as required by the regulatory definition **(European Union, 2019)**. A stepwise framework that brings these elements together is proposed in Figure 6.

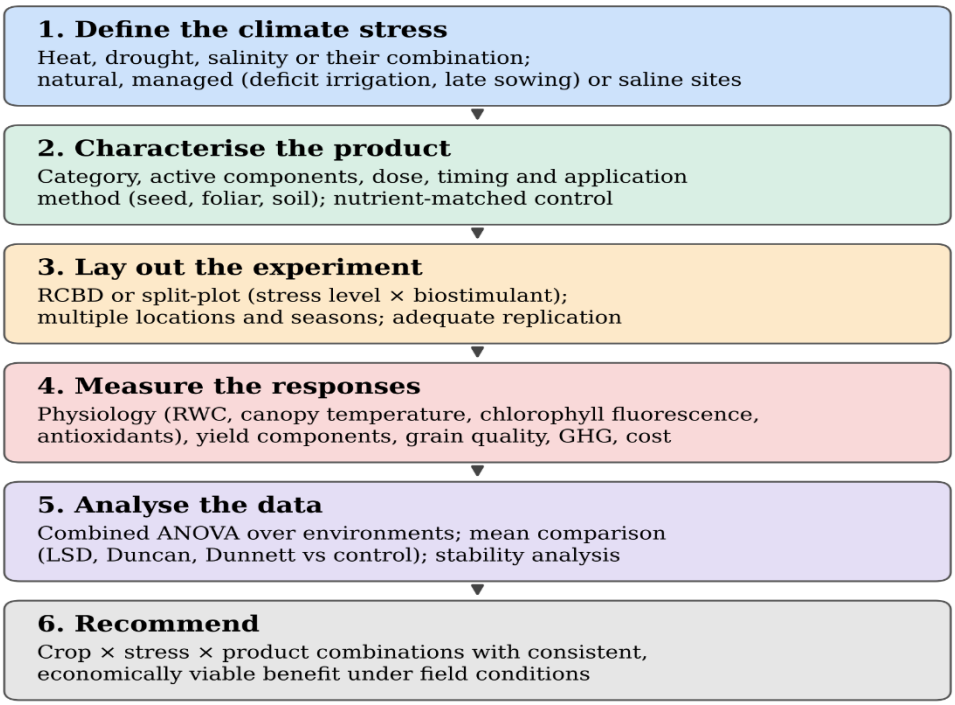


Figure 6. Suggested sequence of steps for testing biostimulants on field crops exposed to climatic stress (RCBD, randomised complete block design; RWC, relative water content; GHG,

greenhouse gas). ***Source: prepared by the author on the basis of the evidence reviewed here and the procedures described by Gomez and Gomez (1984).***

On the basis of the evidence reviewed, the following priorities are proposed. Multi-location and multi-season field trials on the main cereals, legumes and oilseeds should be carried out under natural or managed heat, drought and salinity. Products should be chemically and biologically characterised so that effects can be linked to defined components. Yield should be assessed together with grain quality, including protein and micronutrient contents, given the documented decline in nutritional value under elevated CO_2 **(Leisner, 2020)**. Physiological measurements, such as canopy temperature, chlorophyll fluorescence, relative water content and antioxidant activity, should be combined with yield data to explain variation in response. Economic analysis and, where possible, measurements of greenhouse gas emissions should be included. Finally, the interaction between biostimulants and stress-tolerant cultivars should be examined, since the two approaches are likely to be complementary **(Fahad *et al.*, 2017; Neupane *et al.*, 2022)**.

9. Conclusions

Climate change is already reducing the yield and quality of field crops through higher temperatures, more frequent drought, expanding salinity and elevated CO_2, and these effects are expected to intensify. The review of available evidence indicated that plant biostimulants can reduce the damage caused by these stresses through osmotic adjustment, strengthening of antioxidant defence, hormonal regulation, improved root growth and nutrient uptake, and priming of stress-responsive genes. Every product group considered here, from algal and humic preparations to hydrolysed proteins, microbial inoculants, silicon and chitosan, has helped crops in at least some situations, and some of them can also contribute to mitigation by allowing lower fertiliser inputs. Nevertheless, the responses reported are variable, and most mechanistic knowledge comes from controlled conditions and horticultural crops. Biostimulants should therefore be regarded as one component of climate-smart cropping systems, together with adapted cultivars, sound soil and water management and appropriate sowing dates, rather than as a substitute for them. Well-designed, multi-environment field experiments with characterised products, quality and economic indicators are now required to establish where, when and on which field crops biostimulants can be recommended with confidence.

Conflict of interest

No competing interests are declared by the author.

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