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REVIEW ARTICLE

Nanotechnology and adaptive agronomy for climate–resilient wheat production: A global perspective

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Abstract

Wheat production is increasingly threatened by climate–induced stresses such as terminal heat, drought and erratic rainfall, posing serious risks to global food security. This review synthesises peer–reviewed studies published between 2015 and 2025 to evaluate the synergistic potential of nanotechnology in conjunction with adaptive agronomic practices to enhance a climate–resilient wheat production system. Evidence from multi–location field trials and meta–analyses indicates that improved sowing dates facilitate phenological escape from stress, while nano–enabled fertilisers, pesticides and biostimulants enhance nutrient use efficiency (NUE), enable controlled release and improve abiotic stress tolerance. Concurrently, supplemental water management strategies, like hydrogels and conservation agriculture, mitigate drought stress and enhance water use efficiency (WUE). The crop simulation models, such as decision support system for agrotechnology transfer (DSSAT) and the agricultural production systems simulator (APSIM), further enable scenario analyses and site–specific management recommendations. Despite promising outcomes, reporting yield gains of 15–35 %, significant challenges remain regarding the long–term environmental fate of nanoparticles (NPs), the regulatory processes required for their synthesis and formulation with pesticides or other amendments, as well as the affordability of these technologies for subsistence farmers. Future research should include multi–year and multi–site testing, as well as uniform characterisation of NPs and linking them with artificial intelligence tools and remote sensing techniques mentioned in participatory socio–economic analysis. The collective forward movement of these impacts will ensure safe scaling and adoption of nanotechnologies with adaptive agronomy to help strengthen global wheat resilience to climate variability, as well as contribute towards sustainable agriculture development.

Keywords: adaptive agronomy; climate–resilient; crop simulation; induced stresses; synergistic

Introduction

Wheat (*Triticum* spp.) remains a key foundation of global food security and it is expected that global production will reach 778–790 million tonnes (mt) by 2025 (1). This critical crop helps sustain the diets of more than 2.5 billion people and nearly 20 % of all global caloric intake comes from wheat, which is second only to rice as a source of calories for people in developing countries (2). The semiarid Pacific Northwest region features prominently in the world trade markets not only because it supplies so much wheat, including more than half of total US annual exports, but also because its chemical properties make it sturdier, thus easier to ship across oceans than some other wheats. The geopolitical and agro-economic significance of a stable wheat system is highlighted by the fact that major producers, such as China (approximately 133 mt), India (107 mt), Russia (76 mt) and European Union countries (136 mt), represent about 60 % of the world's output (1).

The productivity of wheat is increasingly challenged by climate–induced stresses. High temperatures (>30 °C) during anthesis and grain filling accelerate phenological development, shorten the grain-filling period and reduce yield by 15–40 % (2). Drought occurring during critical growth stages impair root water uptake and nitrogen acquisition, leading to yield losses of 20–50 % in rain-fed production systems (3). Erratic rainfall, in turn, hinders crop establishment and flowering synchrony, resulting in further yield reductions of 10 to 30 %, particularly in South Asia and sub–Saharan Africa (4). Regional climate models predict that the frequency and intensity of these stressors will intensify by 2030; conventional wheat systems are at risk, with estimates for yield losses ranging from 25 to 35 % under extreme heat scenarios in South Asia and cumulative drought effects already depressing wheat harvest indices by up to 15 % in Eastern Europe (5).

In this context, technology of the very small - nanotechnology - is a game-changing innovation. Nano–fertilisers are nanoparticle-enhanced fertilisers and have been shown to enhance nutrient–use efficiency by 30 % or more with the slow–release and targeted delivery action, which reduces environmental losses of nutrients (6). Field experiments have demonstrated a yield increase of 10–20 % in wheat when using selected abiotic stress protection, including nano –biostimulants and encapsulated nutrients. Internationally, however, a comprehensive assessment of ecological effects, optimal concentrations and legislative frameworks is still necessary (7). In addition to these, adaptive agronomic practices such as adjusting sowing dates, precision irrigation and cultivar diversification have also been effective in mitigating heat and moisture stresses (8). The crop simulation models, such as decision support system for agrotechnology transfer (DSSAT) and agricultural production systems simulator (APSIM), when validated for varied agroecologies, aid in adaptation arrangements with details of sowing windows, which provide stress escape leading to a yield stabilisation advantage of about 15-25 % (9, 10).

This review consolidates peer–reviewed publications from the period 2015–25, with a primary focus on quantitative findings from climate impact assessments, research on nanotechnological innovations and adaptive cultivation strategies. Its goal is also distinct, as it conceptualises an integrated management framework to upscale climate–resilient wheat production worldwide, taking into account existing knowledge gaps and regulatory issues and by laying out future research approaches in light of current food security demands.

Climate Stressors Affecting Wheat and Agronomic Levers

As a result, present–day wheat production is challenged by multiple climate stresses, including terminal heat, drought and unpredictable rainfall, which collectively affect the stability and quality of yields across all agroecological regions (11-13). These climate stressors operate across critical growth stages of wheat and exert strong control over yield stability and grain quality. Heat stress mainly affects reproductive development, whereas drought and rainfall variability disrupt soil–plant water relations, nutrient uptake and physiological functioning (14-16). The combined and interacting effects of these stresses are particularly severe in rainfed and semi-arid production systems, where limited adaptive capacity amplifies production risks**.** A synthesis of reported climate stress impacts and adaptive responses in wheat is presented in Table 1. At the terminal phase, when the temperature exceeds 30 °C during the anthesis and grain–filling periods, photosynthesis is disrupted (19, 20). Phenological development accelerates, shortening the grain–filling period and reducing kernel weight (21). For South Asia and the Mediterranean region, we estimated heat–induced yield penalties ranging from 15 to 40 %. In contrast, Punjabi wheat production declined by around 27 % in response to a heat spike reported over the 2010–2020 period (22). Rainfed wheat systems are particularly limited by drought. Water deficit during the tillering and flowering periods reduces the number of tillers per plant and spikelet fertility, resulting in yield losses that often exceed 50 % in dry environments, such as Sub–Saharan Africa and Central Asia (16). Root water uptake and nutrient assimilation are controlled by water stress and physiological drought appears during moderate soil water deficits owing to stomatal conductance dysfunction (23). The wheat yield also decreases by ~30 % per 100 mm reduction in seasonal rainfall, indicating the high–water sensitivity. Unpredictable rainfall,

Table 1. Comparative analysis of climate stressors affecting wheat: Impacts, physiological mechanisms, regional vulnerability and effective agronomic levers

Climate stressor	Typical yield impact (%)	Key growth stage(s) affected	Core physiological/developmental effects	Regional vulnerability	Effective agronomic levers	Example of successful adaptation	Key references
Terminal heat	15–40	Anthesis and grain filling	Accelerated senescence; reduced grain filling; impaired pollen viability; lower kernel weight	South Asia, Mediterranean and Australia	Early/optimal sowing; heat-tolerant cultivars; foliar protectants; irrigation scheduling	Advance sowing by 10–15 days in the Indo-Gangetic Plains	(9, 10)
Drought	20–50	Tillering, flowering and grain filling	Reduced tillers; lower spikelet fertility; poor root growth; stomatal closure, oxidative stress	South Asia, Sub-Saharan Africa and Central Asia	Drought-tolerant genotypes; hydrogels; deficit irrigation; biochar; conservation tillage	Use of hydrogel + early sowing in North India	(11, 12)
Erratic rainfall	10–30	Sowing, vegetative and flowering	Waterlogging and/or transient drought effect; disturbed phenology; disease outbreaks	South Asia, Africa and Europe	Surface drainage; mulching; residue management; flexible sowing windows	Residue retention + improved drainage, Ethiopia	(13, 14)
Cold/frost stress	5–15	Early vegetative and booting	Delayed germination; spikelet sterility; tissue necrosis	North China, Russia and Northern US	Sowing date adjustment; cold-tolerant cultivars; seed priming	Cold-tolerant genotypes in NE China	(16, 17)
Hail/windstorms	10–25 (localised)	Heading and grain filling	Lodging; mechanical tissue damage; pre-harvest sprouting	Northern America, Europe and Central Asia	Wind breaks; cultivar selection; flexible harvesting	Emergency harvesting, use of resistant lines	(18)
Salinity	10–40	Germination and vegetative	Ion toxicity; osmotic stress; reduced germination; leaf tip necrosis	Coastal South Asia, Mediterranean and Australia	Salt-tolerant cultivars; gypsum amendments; raised beds	Use of salt-tolerant wheat in Gujarat, India	(19, 20)

characterised by alternating periods of drought and waterlogging, disrupts the phenological match and root–zone water availability, further complicating crop management (24). To solve these problems, adaptive agronomy strategies based on optimal sowing date, cultivar selection and phenology manipulation are successful. Manipulation of sowing to avoid periods of terminal heat and drought is a mechanism by which wheat can overcome stress by initiating early growth phases in a favourable climate. Simulation analysis using DSSAT and APSIM also reveals that advancing sowing date by 10-15 days in South Asian systems enhances yield stability by 15-25 %. On the other hand, postponing sowing in cooler temperate zones can be beneficial for aligning growth with the best moisture supply. Resilience is also supported by the selection of cultivars. Genotypes resistant to heat and drought exhibit improved attributes, including deep rooting systems, better osmotic adjustment and enhanced photosynthesis ability under stress (20). Progress in breeding has produced cultivars that can yield 20 % more than standard varieties under heat stress, with phenological tuning to maximise source-sink relationships and resource-use efficiency (25).

Sowing Date Optimisation: Evidence, Modelling and Field Trials

Mechanisms: Escape vs. tolerance strategies

Matching the proper sowing date is a key agronomic approach to reduce climate–induced stresses of wheat production through two mechanisms: escape from stress and tolerance to it (26). The escape mechanism shifts the flowering and grain–filling time to synchronise with a more favourable ambient temperature, thereby avoiding peak terminal heat/drought stress. Empirical grounds indicate that a tying or delayed–ploughing could actually advance phenological events to avoid heat stresses exceeding 30 °C, which would reduce the length of grain filling and kernel weight by nearly 40 %. This technique is particularly successful in areas with predictable stress timing (27). Tolerance mechanisms act in synergy with escape and are based on the use of genotypes having augmented physiological resistance for reaching the maximum potential productivity under detrimental growth conditions remaining at critical periods of growth (28). However, tolerance itself may not be adequate in the absence of seasonal avoidance regulated by sowing time.

Crop modelling tools: DSSAT and APSIM

Crop simulation models, such as DSSAT and APSIM, are routinely used to investigate the effects of changes in sowing date on the development and yield of wheat under different growing conditions (8). These models integrate meteorological, soil and management data. They facilitate scenario testing to predict optimal sowing windows, maximise yield and minimise abiotic stresses. Decision support system for agrotechnology transfer simulations in the Indo–Gangetic plains indicated that shifting sowing by 10–15 days from the current timing relative to historical dates would increase yield stability by 15–25 % via avoidance of terminal heat stress during flowering, as shown in Fig. 1 (29). Similarly, concerning moisture availability and temperature thresholds, APSIM provides specific details that help promote recommended sowing dates in both rainfed and irrigated systems. Such models integrate varietal phenology and make predictions on the impact of climatic variability, delivering region–specific guidelines and not ubiquitous recommendations. Despite their own limitations, such as sensitivity to input quality, difficulties in simulating pest–nutrient interactions and the requirement of calibration under changing climates, they also expose the necessity of ground–truthing with field data (30).

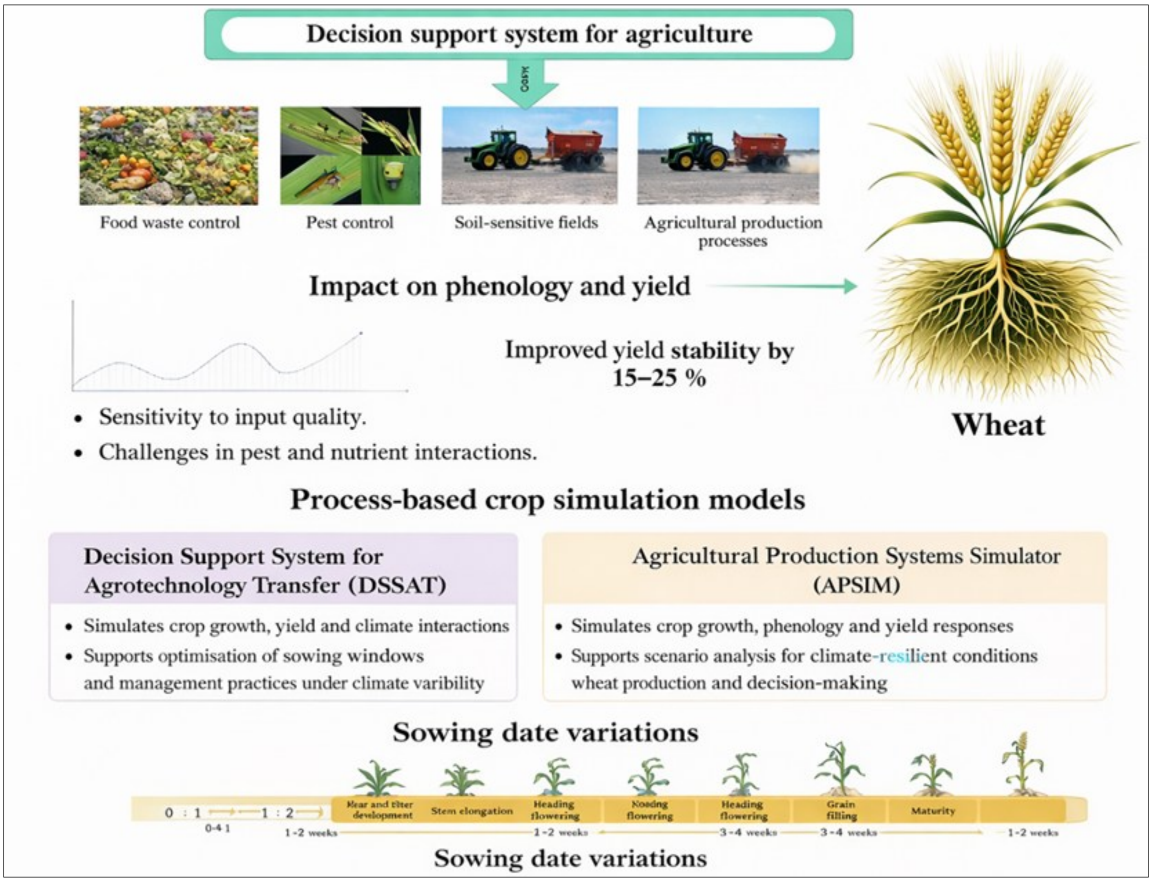

Fig. 1. Process-based crop simulation models (DSSAT and APSIM) support wheat yield optimisation by evaluating sowing date variations, predicting phenology responses and improving yield stability.

Regional recommended sowing windows and meta–analysis

Meta–analyses, which integrate over 30 multi–year trials across South Asia, the Mediterranean and temperate wheat–growing areas, confirm the centrality of sowing date tuning to climate adaptation (31). In line with the former approach, when the sowing date is associated with model–based optimal windows, yields are consistently 10-20 % higher, avoiding warm and dry periods. South Asia does the best sowing from mid–November to early December, thus neatly avoiding late-season terminal heat (32). While Mediterranean environments prefer early October–sown crops to utilise autumn moisture and avoid spring droughts, temperate regions such as Europe and North America favour sowing in early spring when temperatures are warming and soil water is abundant (33). A case study supports these findings; in Punjab, India, early–sown and heat–tolerant cultivars yielded 18 % more compared to conventional practice. Likewise, APSIM simulations applied to the wheat belts of Australia indicate that with no drought at or around flowering, a 15 % increase in final yield is achievable when sowing dates are adjusted to avoid flowering–stage drought (34).

Nanotechnology Applications for Wheat

Types of nanotechnology inputs

Nanotechnology offers promising solutions for improving wheat productivity through versatile nano–based inputs, such as nano-fertilisers, encapsulated pesticides, biostimulants and micro–nutrients using nanoparticles (NPs) as carriers. Nano–fertilisers are engineered particles at submicron to nanometer size, aimed at enhancing the availability and utilisation of nutrients by plants (35). The controlled release of pesticides from a nano–encapsulated form reduces the likelihood of environmental runoff and toxicity to non–target organisms. Nanobiostimulants (NBSs), which are mainly metallic and carbon–based nanomaterials (NMs), play a role in the modulation of plant physiological mechanisms leading to increased growth and tolerance to abiotic stresses. Additionally, nano–carriers are specifically targeted to deliver essential micronutrients, such as zinc and iron, thereby overcoming this widespread deficiency, which is crucial for wheat productivity (36).

Mechanisms of action

Attributed to its unique physicochemical properties, nanotechnology has potential in wheat production due to its distinct physicochemical attributes, such as those that enhance nutrient use efficiency (NUE). The high surface–area–to–volume ratio of NPs, combined with their chemical reactivity, enhances the solubility of nutrients and their uptake by roots. Controlled release formulations enable the sustained delivery of nutrients, reducing losses due to leaching and volatilisation, which can be greater than 30–50 % in conventional fertilisation schedules (37). Additionally, nano–encapsulation aims to achieve the precise release of agrochemicals and reduce environmental pollution and input dose. At the molecular level, NMs interact allosterically with plant signalling pathways, leading to the upregulation of stress–responsive genes and antioxidant enzymes. For example, exposure to NMs activates the reactive oxygen species (ROS) scavenging systems in plants, thereby increasing membrane stability and reducing oxidative damage caused by drought and heat (38). These processes collectively contribute to higher biomass, increased photosynthesis and enhanced grain filling, thereby leading to improved yield under stress.

Evidence from the pot, field and meta–analyses

Evidence for real magic inputs spans from controlled pot experiments to multilocation field trials and large meta–analyses. Pot experiments show that the application of zinc oxide and titanium dioxide NPs at concentrations of 50-100 mg kg^{-1} significantly increases root length density and chlorophyll content. On the basis of field experiments in India and China, yield increases of 10–20 % compared with conventional fertilisation are shown to be possible, together with an increase in NUE of around 25 % and water use efficiency (WUE) gains in a range between 15 and 18 % (39). Meta–analyses of over 50 studies confirm the robust positive impacts of nano–fertilisers and biostimulants on wheat yield and responses to stress, as well as on soil health characteristics (40). Despite these encouraging results, the outcome is not uniformly favourable. Reports of phytotoxicity induced by NPs, e.g., suppressed germination and growth at high dosages, are available from some studies. Furthermore, disturbances to soil microbial communities have been reported, with associated potential risks to the ecosystem. Fine–tuning seems vital because recommended application rates generally are lower than 200 mg kg^{1} for foliar and soil amendments to suppress toxicity (41). There are also unanswered questions about the environmental implications of nanoparticle prolonged existence, accumulation and trophic transfer that warrant transparent monitoring and regulation.

Risk–benefit considerations

However, a balanced analysis includes both the agronomic advantages and the environmental risks. Although nanotechnology has the potential to make an excellent contribution to improving wheat resistance, information gaps remain regarding the long–term environmental fate and safety aspects for food. Further studies should focus on comparative risk–benefit analysis systems with standardised evaluation approaches, as well as potential strategies for control to ensure a safe and sustainable application across different agroecosystems.

Moisture Management: Hydrogels, Soil Amendments and Agronomic Practices

Water management is at the heart of climate–resilient wheat production that seeks to mitigate rising water deficit trends due to variable rainfall and prolonged droughts (28). Synthetic and natural polymer–based hydrogels are characterised by their high water–absorbing and retaining ability, which is mainly involved in improving soil moisture availability to plant roots. Their mechanism of action involves the absorption of water when moist and its slow release during drought periods, resulting in a positive effect on seed germination and early seedling establishment under water–restrictive conditions (12). Field experiments demonstrate that treating wheat with hydrogels can increase seed germination by 20 % and enhance wheat biomass accumulation under drought stress by 10-15 % compared to untreated controls. In addition to water adsorption, hydrogels also act as stabilisers for soil structures, which may lead to reduced irrigation frequency and ecological or agronomic benefits (42). However, the long–term effects of hydrogel on the soil microbial community remain to be investigated, to reveal whether there are structural changes in the microbial community or specific functional groups driven by the stability of hydrogel. In addition to hydrogels, soil conditioners (organic amendments and biochar) also contribute to an increased water–holding capacity through improvements in overall porosity and the formation of larger aggregates in the soil, with a contribution from FC reaching up to 10-25 %. These modifications also enhance continuous nutrient availability and microbial activity, both of which are important in sustaining N cycling and soil health (43). The application of biochar at rates of 10-20 t ha^{-1} has been shown to enhance wheat yield by 12-18 % under drought conditions, mainly attributed to increased water retention and nutrient availability (44). Although these interventions have shown promise, their scalability and cost-effectiveness, particularly among smallholder farmers, need to be critically evaluated to guide broader adoption.

Moisture conservation is closely linked to the adoption of conservation agriculture practices, including reduced tillage (such as no–tillage or minimum tillage), mulching and the retention of crop residues. By placing organic or synthetic materials on the soil surface, water evaporation is reduced by 25-40 %, soil temperature is moderated and weed growth is inhibited, providing an overall improvement in WUE (45). This residual retention also helps to maintain soil cover, favouring the infiltration process and minimising runoff and erosion (46). However, they may have some trade–offs (which differ between conditions) and attending practices that should complement each other in implementation. Deficit irrigation (DI), the controlled application of water at critical growth stages, presents itself as a practical strategy to maximise water productivity without incurring major yield penalties. Field testing showed that it is possible to save 30-40 % of water compared with fully irrigated plots, while achieving wheat yields from 85 and up to 90 % of that produced under full irrigation; these results are decisive for increasing WUE in water–limited environments (47).

Integrative Approaches: Combining Sowing Optimisation, Nano –Inputs & Moisture Technology

Integrating agronomic interventions by simultaneously combining sowing date manipulation, inputs applied through nanotechnology and improved water availability could be a promising approach to enhance wheat resilience under climate stress (48). Recent findings from various agroecological settings suggest that these components act synergistically and result in yield increases and stress amelioration responses that are more pronounced than those obtained with any single intervention alone. For example, sowing early to match phenology with optimum climatic windows minimises exposure to terminal heat and drought stresses. Meanwhile, nano–based fertilisers and biostimulants enhance the availability of nutrients under critical stress conditions to improve physiological processes (49). In conjunction with these, soil moisture stabilisation at the root level by hydrogels and conservation agriculture (CA) practices are activities that support improved WUE and metabolic robustness. These returns are supported by empirical evidence: multi–location studies conducted across South Asia on adding an adjusted sowing date, as well as the application of nano–fertilisers and amendments with hydrogel (Fig. 2), demonstrate that grain yield can increase by 20-35 % compared to conventional practices (50). Such integrated products are claimed to enhance WUE by 25 %, primarily due to greater water retention and accurate nutrient application. Physiological measurements demonstrate the underpinning of these synergies through maintained photosynthetic rates and the amelioration of oxidative stress indicators, providing a mechanistic basis for the agronomic benefits (51). To comprehensively study these complex and multifaceted systems across a range of climates, factorial experiments with sound design are necessary. The designs of choice in most instances are split–plot treatments, where the reporting of sowing dates is configured as level one blocks and the design of nano–input dose levels and moisture management strategies is randomised within level two subplots. Here, multi-year, multi–location experiments combining detailed phenotyping, which includes the measurement of yield components, water potential, nutrient uptake and stress biomarkers, are needed to unravel interaction effects and tailor combinations for different environments (52). Crop growth models, such as DSSAT and APSIM, have emerged as important tools with the addition of nanotechnology components and soil hydrodynamics to simulate integrated scenarios under projected climate conditions (53). These models enable the exploration of alternative sowing windows, nano–input regimes and moisture conservation strategies to arrive at robust yet context–specific management options. The inclusion of dynamic feedback among soil moisture, nutrient status and phenological stages is essential for realistic scenario predictions (54). Nevertheless, the operationalisation of these integrated pathways at scale presents challenges such as differences in resource availability, complexities in management coordination and limitations on initial investments, especially in smallholder settings. These challenges can be met through the participatory engagement of users, policies that support access to tools and the development of decision–making support aids adapted to local conditions. Graphical models explaining the interaction among phenology, nanochemistry and moisture dynamics could help transfer knowledge and trigger use to increase adoption and effects.

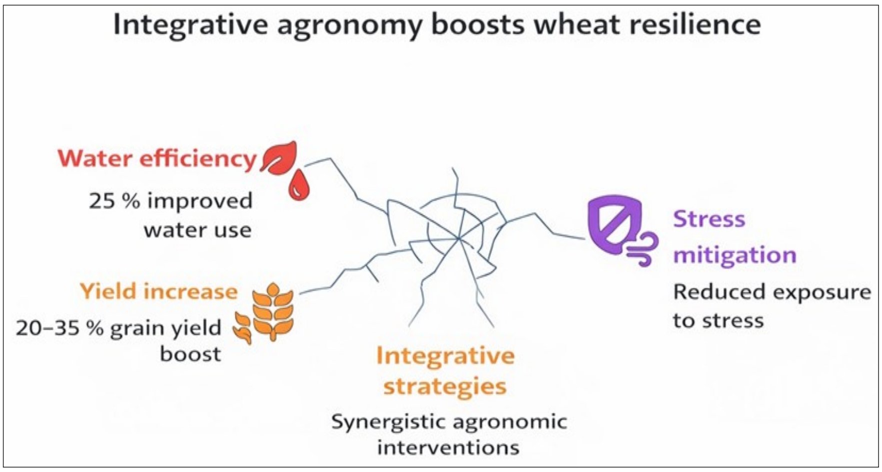

Fig. 2. Integrative agronomic strategies enhance wheat resilience by improving WUE by 25 %, boosting grain yield by 20–35 % and mitigating environmental stress, demonstrating the synergistic benefits of combined interventions.

Risks, Regulatory and Socio–Economic Considerations

Despite promising developments in the use of nanotechnology for wheat production, several environmental, regulatory and socio–economic issues need to be carefully analysed before it can be recommended at a large–scale level. The environmental behaviour of NPs is not well understood, particularly with respect to their fate, transformation, bioaccumulation and potential ecotoxicological effects (55). Research suggests that NPs may aggregate and interact with soil microbial communities, potentially disrupting biogeochemical cycles essential for maintaining soil health. Several studies have documented the acute toxicity of metal oxide NPs on keystone soil organisms such as beneficial microbes and earthworms, suggesting potential adverse impacts to soil biodiversity and ecosystem functions at higher NP accumulation beyond tipping points (56). However, the translocation of NPs in plants and their accumulation in edible parts remain a significant concern for food security, with some evidence suggesting possible genotoxicity at high exposures. This highlights the need for long–term and comprehensive environmental monitoring, along with advanced NP tracking techniques (57).

The existing regulations for agricultural NMs are in their infancy and there is no comprehensive guideline for their identification, registration and post–application monitoring at both national and international levels. For example, the European Union has already promulgated a regulatory action under its REACH (Registration, Evaluation, Authorisation & Restriction of Chemicals) regulation on NMs safety and the US EPA requires consideration of NMs as part of its pesticide registration process. Despite this, some countries still lack specific regulations for nanotechnology and therefore do not facilitate or allow market access, which undermines farmer confidence (58). The differences in risk perceptions among regulators, researchers and stakeholders further complicate matters. There is a pressing need for internationally harmonised standards in nanoparticle characterisation, toxicity threshold determination and residue exposure limits to facilitate responsible implementation (59). Economically, the nanoformulated inputs generally have higher upfront costs as compared to traditional agrochemicals, creating barriers to adoption, particularly for resource–poor smallholder farmers. Long–term cost–benefit analyses from field trials conducted in India and China show that yield increases of 10-25 % can recover the investment over a series of cropping cycles; however, forward costs and supply chain gaps remain key barriers (60, 61). In–depth economic assessments that differentiate between smallholder and commercial farming systems are required to optimise adoption strategies and subsidy mechanisms. Efficient risk reduction may involve integrated solutions, such as improved dosing schemes, environmental risk assessment and the introduction of biodegradable or less persistent nanoformulations. At the same time, extension and participatory services are key to closing knowledge gaps, raising awareness among farmers about the advantages and risks of adoption as well as showing returns on investment, thus building trust and uptake. Policymakers and researchers should co–teach guidance that combines advances in technology with socio–environmental protections, ensuring access for all on an equitable basis while maintaining long–term viability (62).

Knowledge Gaps and Future Research Agenda

Need for multi–location, multi–year trials and long–term monitoring

Large knowledge gaps limit the dissemination and scaling up of nanotechnology integration with climate-resilient agronomy for wheat production. First, there is a lack of extensive, multi–site, multi–year field experiments that reflect spatial and temporal variation in agroclimatic conditions. Most current studies are based on short–term, localised experiments, making extrapolation across different environments and future climatic conditions challenging (63). Widespread regular long–term monitoring programs are necessary to further contribute to understanding the chronic effects of nano–input accumulation on soil health, plant-related physiological responses and ecosystem services (64). Common protocols for the fate, residue and ecotoxicity of NPs are urgently required to support environmentally safe and sustainable nanotechnology (57). The following are research questions deserving further investigation: What is the impact of repeated applications of NPs on soil microbial diversity across seasons? At what nanoparticle accumulation level does an ecotoxicological risk exist? To what extent are nano–fostered agronomic gains comparable in contrasting climatic and soil contexts?

Farmer–centric cost–benefit analyses and adoption barriers

Socio–economic studies on farmer perceptions, explicit cost–benefit models and certain barriers to the adoption of nano–enabled agriculture technologies are underdeveloped but necessary for in–depth scaling up innovations (65). There is empirical evidence from participatory trials, as well as socio–economic surveys, that high entry costs, lack of access, inadequate experience and perceived risk are among the major constraints to smallholder adoption in developing areas (66). Future work should develop context–specific adoption roadmaps based on cost/efficiency approaches, integrating yield benefits combined with input costs, labour savings and ecosystem service enhancement. Some of these questions include: What economic incentives or policy stimuli are most effective in fostering the adoption of smallholder nano–inputs? What is the role of social networks in technology diffusion? Interdisciplinary collaborations among agronomists, economists and social scientists are required to fill this gap, along with robust extension systems.

Development of standards for nano–inputs and regulatory harmonisation

A lack of globally harmonised standards related to production, characterisation, application rates and allowed residues of nano–inputs is a barrier to regulatory approval and market penetration (67). The development of such robust quality benchmarks and exposure safety thresholds in humans through advanced characterisation methods (size distribution, functionalization) is needed. In addition, the cooperation of international regulatory authorities, scientific societies and industrial players should be harmonised to develop policies that favour environmental protection without impeding technological advances. It should be investigated: What is the impact of standardised nanoparticle characterisation on inter–lab differences? What are the most suitable risk assessment systems that strike a balance between innovation and precaution?

Integration with artificial intelligence (AI) and remote sensing technologies

Growing digital technologies, including AI and remote sensing, promise capabilities for enhanced nano–input application and adaptive agronomic management in near real–time (68). The combination of AI–based prediction models and multi–source remote sensing data facilitates the accurate targeting of nano–fertiliser application, irrigation schedules and sowing dates, thus improving resource use efficiency and sustainability. Sensor networks and imaging platforms have enabled the real–time monitoring of crop stress indicators, soil moisture and nutrient dynamic information to make responsive modifications in response to site–specific variability (69). Follow–on work is needed to develop interoperable AI models that fuse various datasets to provide actionable insights at the farm level, thereby unlocking the adoption of nanotechnology applications and enhancing climate resilience (70).

Enhancing Collaboration, Data Sharing and Open Science

Addressing these knowledge gaps requires enhanced interdisciplinary cooperation among botanists, nanotechnologists, agronomists, computer scientists, economists and decision-makers. In this context, Open Science (OS) principles are critical for improving transparency, reproducibility and equitable access to scientific knowledge. The establishment of open-access data repositories, standardised metadata frameworks and interoperable platforms can facilitate cross-disciplinary integration of experimental, modelling and socio-economic datasets, thereby enabling robust meta-analyses and evidence synthesis. Open sharing of protocols, datasets and modelling outputs also supports the validation of nanotechnology-based and climate-adaptive agronomic interventions across diverse agroecological regions. Moreover, OS practices enhance stakeholder engagement by improving access to research outputs for policymakers, extension agencies and farming communities. Participatory and open innovation frameworks support co-creation of climate-resilient solutions, strengthen trust in emerging technologies and accelerate knowledge translation into practice. By embedding OS principles within climate-smart wheat research, the development and deployment of safe, scalable and equitable production technologies can be significantly accelerated at the global level.

Conclusion

This review highlights the synergistic potential of nanotechnology and adaptive agronomy for enhancing climate-resilient wheat production. Increasing incidences of terminal heat, drought and erratic rainfall threaten global wheat yields, underscoring the need for integrated resource management strategies. Optimised sowing dates facilitate phenological escape from stress, while nano-based inputs improve nutrient-use efficiency, targeted delivery and stress tolerance. Complementary moisture management practices, including hydrogels, soil amendments and conservation agriculture, further stabilise soil water availability. Evidence from multi-site experiments and meta-analyses indicates that these combined approaches can increase wheat yields by 15–35 %, alongside improvements in water-use efficiency and physiological resilience. Crop simulation models such as DSSAT and APSIM support the development of site-specific management strategies across diverse agroecological regions. However, key challenges remain, including uncertainties regarding the long-term environmental fate of NPs, regulatory inconsistencies and socio-economic barriers to adoption. Addressing these gaps through long-term field validation, standardisation of nano-input quality metrics and integration of digital agriculture tools will be essential. Coordinated interdisciplinary research and supportive policy frameworks are therefore critical for the sustainable scaling of climate-smart wheat production systems.

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Authors' contributions

MAK conceived the idea, designed the structure of the review and contributed to the global perspective on nanotechnology applications. SV compiled literature on adaptive agronomy practices with special emphasis on Indian agro-climatic conditions. MK analysed and integrated recent advancements in wheat physiology and climate-resilient crop management. SSP focused on policy implications, field-level applications and sustainability aspects. DP coordinated the overall manuscript preparation, supervised the writing process and critically revised the final draft. SKY contributed in data organisation, reference management and assisted in drafting and editing of the manuscript. All the authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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