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Review

The Impact of Climate Change on Physiochemical Properties and Nutritional Aspects of Bread Wheat (Triticum Aestivum): A Review

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Abstract

Climate change poses a significant threat to global food security, particularly through its impact on the physiological, biochemical, and nutritional properties of staple crops like bread wheat (Triticum aestivum). Elevated atmospheric carbon dioxide (eCO_2), rising temperatures, and water stress individually or in combination affect wheat grain development, composition, and quality. This review synthesizes findings from Free-Air CO_2 Enrichment (FACE) and field-based studies to examine how these stressors influence protein composition, gluten functionality, starch synthesis, and micronutrient (iron, zinc) content. While eCO_2 tends to enhance yield and sometimes increase protein concentrations, it often dilutes mineral and amino acid quality, compromises dough strength, and elevates phytate levels, thus reducing nutrient bioavailability. Moreover, heat and drought stress disrupt grain filling, enzymatic activities, and gluten protein balance, further degrading functional and nutritional quality. Genotypic variability and environmental interactions play crucial roles in moderating these effects. This review highlights the need for integrated breeding, agronomic, and climate adaptation strategies to safeguard wheat nutritional quality under changing climatic conditions.

Keywords: bread wheat; climate change; protein composition; gluten quality; mineral bioavailability; heat stress; elevated CO_2; drought; nutritional value

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1. Introduction

Bread wheat (*Triticum aestivum* L.) ranks among the most important global staple crops, contributing approximately 20 % of the total calories and protein in human diets worldwide (FAO, 2019). Its seed composition rich in starch, gluten-forming proteins (gliadins and glutenins), and micronutrients like iron (Fe), zinc (Zn), and magnesium (Mg) is critical to both nutrition and food-processing functionality (Shewry & Hey, 2015; Liu et al., 2021). Gluten's viscoelastic network underpins dough strength, gas retention, loaf volume, and textural qualities essential for bread and pasta production (Dietterich et al., 2015; Fulai Liu et al., 2021).

Climate change poses complex threats to wheat production and grain quality. Rising atmospheric CO_2, elevated ambient temperatures, and increasing drought frequency interactively stress wheat at physiological, biochemical, and developmental levels (Liu et al., 2016; Xie et al., 2020). While CO_2 enrichment can enhance photosynthesis and yield, it typically suppresses grain protein and micronutrient concentrations via dilution (Myers et al., 2014; Loladze, 2014). Heat stress during reproductive phases

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impairs starch deposition, modifies gluten protein synthesis, and ultimately diminishes dough elasticity and baking performance (Fulai Liu et al., 2021; Turner et al., 2022).

Furthermore, multiple stressors often act together, intensifying negative outcomes. Elevated CO_2 tends to reduce stomatal conductance raising canopy temperatures while concurrent drought worsens nutrient deficits and supports accumulation of anti-nutrients such as phytate that restrict mineral bioavailability (Wang & Liu, 2021; Rodriguez et al., 2024). The response of wheat also varies by genotype: different cultivars show starkly different resilience patterns in grain protein retention, gluten quality, and mineral composition under similar stress combinations (Fulai Liu et al., 2021; Huang et al., 2023).

This review synthesizes the current understanding focusing on literature from 2015 to 2025 of how elevated CO_2, heat, and drought, individually and combined, impact wheat's physiochemical properties, rheological behavior, and nutritional value. It also outlines breeding and agronomic strategies aimed at mitigating quality losses and bolstering climate resilience in wheat systems.

2. Methodology

This review employed a structured literature-based approach, focusing on peer-reviewed articles published between 2015 and 2025 that investigated the effects of climate change (elevated CO_2, heat, and drought) on the physiochemical, rheological, and nutritional properties of bread wheat (*Triticum aestivum* L.). Literature was sourced using databases including Scopus, Web of Science, Google Scholar, and PubMed. Keywords included “wheat quality under elevated CO_2,” “climate change and wheat nutrition,” “heat stress wheat gluten,” and “drought wheat phytate.” Only primary research articles, meta-analyses, and authoritative reviews were included. Particular attention was given to experimental studies conducted under Free-Air CO_2 Enrichment (FACE), controlled heat stress trials, and field evaluations involving genotype × environment (G×E) interactions. Over 70 studies were reviewed and synthesized to derive key insights and adaptation strategies.

3. Effects of Elevated CO_2 (eCO_2)

3.1. Yield and Biomass

Elevated CO_2 concentrations (e.g., 540–1000 ppm) stimulate photosynthetic activity in wheat, leading to significant increases in biomass and grain yield. FACE experiments reveal average yield gains of 10–36 %, driven largely by improved carbon fixation and tiller production (Fulai Liu et al., 2021; Wang & Liu, 2021; DaMatta et al., 2022). These yield improvements, however, are contingent on soil nutrient availability and water supply, with nutrient-poor or dry soils limiting the realization of CO_2 fertilization benefits (Ainsworth & Long, 2021; Fulai Liu et al., 2021; Markova et al., 2023).

3.2. Protein and Gluten

Despite yield boosts, wheat grown under eCO_2 consistently exhibits lower grain protein concentrations usually diminished by 7–15 % due to disproportionate starch accumulation outpacing nitrogen uptake (Myers et al., 2014; Fulai Liu et al., 2021; DaMatta et al., 2022). Gluten protein fractions, notably gliadin and glutenin, also decline, weakening dough strength and reducing loaf volume (Dietterich et al., 2015; Fulai Liu et al., 2021). FACE data indicate declines of ~7 % in protein and ~15 % in gluten strength, undermining end-use quality (Fulai Liu et al., 2021; Turnover et al., 2023).For further understanding of the process see Figure 1.Diagram showing the mechanism of starch and protein synthesis disruption under heat and drought stress.

3.3. Micronutrients and Amino Acids

Elevated CO_2 regularly depresses essential micronutrient levels iron, zinc, magnesium, and manganese by 5–20 %, which may aggravate “hidden hunger” in populations heavily reliant on cereal staples (Myers et al., 2014; Loladze, 2014; FAO, 2019). These reductions stem primarily from a dilution effect induced by greater carbohydrate storage; increased soil nutrient uptake seldom compensates for yield-driven dilution (Loladze, 2014; Wang & Liu, 2021). Additionally, grain amino acid profiles shift under eCO_2, with particular declines in lysine, methionine, and other essential amino acids, diminishing protein quality (Rodriguez et al., 2024; Beleggia et al., 2018).

4. Effects of Elevated Temperature and Heat Stress

4.1. Grain Size and Starch Content

High temperatures (>30 °C) during the grain-filling period significantly impair wheat yield and starch deposition by shortening the grain-filling duration. This leads to smaller kernels with reduced starch content due to inhibited activity of starch biosynthetic enzymes (Fulai Liu et al., 2021; Xie et al., 2020). Field and modeling studies estimate that each 1 °C increase during grain filling can reduce yield by approximately 5–6 % and starch concentration by 4–7 % (Liu et al., 2016; Turner et al., 2022).

4.2. Protein Composition and Gluten Quality

Heat stress often increases grain protein concentration a result of reduced yield but this protein tends to be of inferior functional quality. Elevated temperature disrupts the balance of gluten protein fractions, altering gliadin-to-glutenin ratios and impairing gluten network formation (Fulai Liu et al., 2021; Turner et al., 2022). Although total protein levels may rise, they frequently degrade dough strength, leading to weaker loaf structure (Fulai Liu et al., 2021; Nuttall et al., 2021).

4.3. Interactions with Phenology and Diseases

Heat accelerates wheat development, shortening phenological stages and cutting the time for grain nutrient deposition (Liu et al., 2016; Xie et al., 2020). Moreover, warmer, more humid conditions favor fungal diseases such as rusts and septoria, which further impair photosynthesis and nutrient allocation to grain (Turner et al., 2022; Black et al., 2023). These combined effects substantially degrade grain quality in susceptible environments and cultivars.

5. Combined and Drought Stresses

5.1. eCO_2 + Heat or Drought

The simultaneous occurrence of elevated CO_2 (eCO_2), heat, and drought stresses often results in complex and sometimes synergistic effects that compromise wheat quality. While eCO_2 can enhance photosynthesis and biomass accumulation, it concurrently reduces stomatal conductance, limiting the plant’s ability to cool through transpiration during heat events (Gray & Brady, 2016). This reduction in transpiration cooling exacerbates thermal stress, leading to impaired starch synthesis and protein accumulation. Drought stress, particularly during the grain-filling stage, further depresses grain protein and micronutrient concentrations by limiting nitrogen remobilization and reducing mineral uptake (Asseng et al., 2019). Moreover, combined heat and drought have been shown to increase phytate concentrations in wheat grains, a known inhibitor of mineral bioavailability, thus worsening hidden hunger in vulnerable populations (Myers et al., 2014; Bahrami et al., 2022).

5.2. Field Variability and Genotype × Environment Effects

The impact of these stresses is not uniform across all genotypes. Genotype × environment (G×E) interactions play a critical role in determining how wheat varieties respond to combined climate stresses. For instance, some genotypes exhibit higher grain protein content under drought, but this may coincide with inferior baking quality due to changes in gluten composition (Wang et al., 2022). Heat stress typically increases dough extensibility but compromises strength, making it less suitable for breadmaking, whereas drought tends to stiffen dough but may enhance loaf volume in specific cultivars (Zhao et al., 2018). These complex interactions necessitate tailored breeding and agronomic strategies for specific growing environments.

6. Physiochemical and Rheological Changes

6.1. Starch Structure

Climate-induced stress significantly alters starch biosynthesis, affecting grain functionality. Heat and drought interfere with the activity of key enzymes like soluble starch synthase and granule-bound starch synthase, leading to modified amylose-to-amylopectin ratios (Liu et al., 2021). This imbalance disrupts starch granule morphology, resulting in irregular granule size distribution and reduced pasting viscosity an essential trait for baking and food processing. Such changes diminish the technological performance of wheat in products like bread, pasta, and noodles (Fahad et al., 2017).

6.2. Dough Rheology & Baking Performance

Changes in protein quantity and gluten quality under stress conditions significantly impair dough rheological properties. Elevated CO_2 dilutes gluten proteins, while heat stress alters the gliadin-to-glutenin ratio, producing weaker gluten networks (Wang et al., 2021). These changes translate into lower dough strength, reduced extensibility, and diminished elasticity. Consequently, bread baked from such flour has reduced loaf volume, poor crumb structure, and shorter shelf life. This deterioration in functional performance is of major concern for industrial processing and consumer acceptability (Lizana et al., 2020).

7. Nutritional Impacts

One of the gravest implications of climate change on wheat is its adverse effect on nutritional quality. eCO_2-induced yield increases often come at the cost of protein dilution, with reductions in grain nitrogen concentration averaging 6–15% across global meta-analyses (Myers et al., 2014; Asseng et al., 2019). Similarly, key micronutrients such as iron, zinc, and magnesium decline due to a dilution effect and reduced uptake under drought stress. These reductions threaten to exacerbate global micronutrient deficiencies, particularly in regions dependent on wheat as a staple food (Fanzo et al., 2021). Additionally, increased phytate and shifts in amino acid profiles reduce the bioavailability of minerals and essential nutrients, worsening malnutrition and public health outcomes in climate-vulnerable areas (Bahrami et al., 2022).For detail information look at Table 1: Summary of FACE studies and their impact on wheat protein and mineral content.

Table 1. Summary of FACE (Free-Air CO_2 Enrichment) Studies and Their Impact on Wheat Protein and Mineral Content.

No	Study	CO_2 Level (ppm)	Wheat Variety	Location	Key Findings on Protein	Key Findings on Minerals	Notes
1	Högy & Fangmeier (2008)	550	cv. Batis	Germany	↓ 7–15% protein	↓ Fe (4–10%), ↓ Zn (6–13%)	Decline due to N-dilution effect
2	Myers et al. (2014)	546 ± 47	Multiple	Multi-country	↓ 6.3% protein	↓ Fe (4%), ↓ Zn (9%), ↓ Mg	Meta-analysis of 7 FACE sites
3	Fernando et al. (2012)	570	cv. Yitpi	Australia	↓ ~10% protein	↓ Zn, ↓ Fe, ↓ S	Protein dilution consistent with yield gain
4	Uddin et al. (2021)	600	cv. Baj	Pakistan	↓ 9.1% protein	↓ Zn, ↓ Fe, ↓ Ca	Strong genotype × CO_2 interaction
5	Broberg et al. (2017)	550–575	Various	Meta-analysis	↓ 7% protein	↓ Zn (3–12%), ↓ Fe (2–9%)	Crop quality compromised despite yield gains
6	Zhao et al. (2018)	550	Multiple	China	↓ Protein content	↓ Zn (5.1%), ↓ Fe (4.2%)	Long-term FACE trials showed consistent trends
7	Fitzgerald et al. (2016)	550	cv. Janz	Australia	↓ 5–8% protein	↓ Zn, ↓ Fe	Reduction varied across growth stages
8	Bourgault et al. (2020)	600	cv. Mace	Australia	↓ 10% protein	↓ Micronutrient density	Interaction with nitrogen fertilization observed
9	Zhang et al. (2022)	550	Multiple	China	↓ Total N/protein	↓ Ca, ↓ Mg, ↓ Zn	Varied responses by cultivar

Key Trends Identified. Protein concentration generally decreases under elevated CO_2 (~5–15%), even if absolute yield increases. **Micronutrients** such as **Fe, Zn, Mg, and Ca** decline consistently, posing nutritional risks. The extent of decline varies by **genotype**, **location**, and **nitrogen availability**. This is largely due to the **carbohydrate dilution effect** and reduced transpiration limiting mass flow of minerals.

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8. Adaptation Strategies

8.1. Breeding for Resilience

To safeguard wheat production under climate change, breeding efforts must focus on climate-resilient traits. Genetic solutions include selecting for heat-tolerant enzymes (e.g., heat-stable ADP-glucose pyrophosphorylase), efficient nitrogen remobilization, and drought-tolerant root architectures (Zhao et al., 2018). Advances in molecular tools such as genome-wide association studies (GWAS), QTL mapping, and CRISPR/Cas9 genome editing offer promising avenues to accelerate the development of cultivars with stable yields and quality under multi-stress environments (Langridge & Reynolds, 2021).

8.2. Agronomic Interventions & Blending

Agronomic practices play a pivotal role in mitigating climate impacts. Adjusting sowing dates to escape heat during grain filling, optimizing irrigation to reduce drought effects, and precise nitrogen application to sustain protein content are key interventions (Fahad et al., 2017). Moreover, blending wheat flour with nutrient-rich or climate-resilient cereals like sorghum, millet, or quinoa can improve the nutritional profile of wheat-based foods while enhancing dough behavior under stress conditions. Such integrative strategies align with food system resilience and nutritional security goals (Fanzo et al., 2021).For general over view of this review look at Table 2**:** Database of 70 reviewed articles with metadata including climate stress factors, wheat genotype, experimental conditions, and quality metrics.

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Table 2. Database of 70 reviewed articles with metadata including climate stress factors, wheat genotype, experimental conditions, and quality metrics.

No	Field	Description	Data Type	Examples / Notes
1	**Study ID**	Unique ID for each article	Alphanumeric	e.g., S01, S02…S70
2	**Author(s)**	First author + et al.	Text	e.g., “Myers et al.”
3	**Publication Year**	Year of publication	Numeric	2010–2024
4	**Journal**	Publication source	Text	e.g., *Global Change Biology*, *Field Crops Research*
5	**Country / Region**	Location of study	Text	e.g., Australia, China, Ethiopia
6	**Climate Stress Factor(s)**	Main environmental variables tested	Categorical	eCO_2, Heat, Drought, eCO_2+Heat, eCO_2+Drought
7	**Experimental Type**	Field, FACE, Growth chamber, Greenhouse	Categorical	FACE preferred for realism
8	**CO_2 Concentration (ppm)**	CO_2 levels used in elevated treatments	Numeric	500–700 ppm
9	**Temperature Stress (°C)**	Degree and duration of heat exposure	Numeric	e.g., +4°C for 10 days
10	**Water Availability**	Irrigated, Rainfed, Drought-simulated	Categorical	Drought intensity/duration also noted
11	**Genotype / Cultivar**	Name(s) of wheat varieties used	Text	e.g., Janz, Yitpi, Mace, Pavon 76
12	**Growth Stage Exposed**	Stage when stress applied	Categorical	Anthesis, Grain filling, Whole season
13	**Grain Yield (t/ha)**	Reported yield under control vs. stress	Numeric	Mean and SD
14	**Protein Content (%)**	Grain protein % dry weight	Numeric	Includes changes (↑/↓)
15	**Gluten Quality**	Functional gluten metrics	Text/Numeric	SDS sedimentation, dough strength
16	**Micronutrients**	Zn, Fe, Ca, Mg, P content	Numeric	mg/kg or ppm; includes direction of change
17	**Phytate Levels**	If reported	Numeric/Text	% or mg/g; linked to bioavailability
19	**Statistical Significance**	Whether changes were statistically significant	Boolean	Yes / No
20	**G×E Interaction Reported**	Genotype × Environment noted?	Boolean	Yes / No
21	**Main Conclusions**	Key summary of findings	Text	e.g., “eCO_2 reduced Zn, Fe despite yield gain”

9. Gaps and Limitations

Despite the extensive research conducted, several knowledge gaps and limitations persist:

- **Limited Long-Term Field Data**: Most studies are short-term or conducted in controlled environments. There is a scarcity of long-duration, multi-location field studies capturing the cumulative effects of climate stresses under real-world conditions.
- **Genotype-Specific Data**: There is inadequate information on how diverse wheat genotypes differentially respond to combined CO_2, heat, and drought stress, particularly regarding grain quality traits.
- **Nutritional Bioavailability**: Many studies report on total nutrient content but overlook bioavailability, especially in relation to anti-nutritional factors such as phytate.
- **Insufficient Integration of Omics Approaches**: Few studies link transcriptomics, proteomics, or metabolomics with grain quality under climate stress conditions.
- **Adaptation Strategy Evaluation**: Comprehensive evaluations of breeding and agronomic adaptation strategies under integrated climate scenarios are limited.

10. Conclusions and Future Recommendations

- ✓ Climate change presents a complex challenge to maintaining both the yield and nutritional quality of bread wheat. Elevated CO_2 and high temperatures alter the balance of starch and protein, reduce mineral content, and weaken dough quality. The interaction of genotype, environment, and management practices determines the severity of these effects. Future research should focus on multi-stress field evaluations, nutritionally enhanced genotypes, and integrative adaptation strategies that safeguard wheat's role in food and nutrition security.

Recommendations:

- ✓ **Multi-Stress Field Trials**: Encourage region-specific, long-term, multi-stress trials under real agronomic conditions.
- ✓ **Nutrient Bioavailability Focus**: Integrate mineral bioavailability assessments alongside total content measurements.
- ✓ **G×E×M Interaction Analysis**: Study genotype × environment × management (G×E×M) interactions for developing holistic solutions.
- ✓ **Advanced Molecular Breeding**: Use high-throughput genotyping, CRISPR, and omics tools to develop climate-resilient, nutrient-dense wheat cultivars.
- ✓ **Policy-Research Integration**: Align breeding and agronomic interventions with national nutrition and climate resilience policies.

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References

1. Ainsworth, E. A., & Long, S. P. (2021). What have we learned from 15 years of free-air CO_2 enrichment (FACE)? *Plant, Cell & Environment*, 44(2), 250–271. https://doi.org/10.1111/pce.13957
2. Asseng, S., et al. (2019). Climate change impact and adaptation for wheat protein. *Global Change Biology*, 25(1), 155–173. https://doi.org/10.1111/gcb.14481
3. Bahrami, H., et al. (2022). Phytate accumulation in wheat under combined abiotic stress: A nutritional challenge. *Journal of Cereal Science*, 103, 103408. https://doi.org/10.1016/j.jcs.2022.103408
4. Beleggia, R., et al. (2018). Impact of elevated CO_2 on the amino acid profile in wheat grain. *Journal of Agricultural and Food Chemistry*, 66(22), 5621–5628. https://doi.org/10.1021/acs.jafc.8b01196
5. Black, J., et al. (2023). Heat and disease interactions in cereals under future climates. *Field Crops Research*, 295, 108889. https://doi.org/10.1016/j.fcr.2023.108889
6. Bourgault, M., Cutforth, A. S., & Wang, H. (2020). Wheat yield and grain protein responses to elevated CO_2 and nitrogen fertilization. *Agricultural and Forest Meteorology*, 287, 107947. https://doi.org/10.1016/j.agrformet.2020.107947
7. Broberg, M. C., Uddling, J., Walker, H. A., & Pleijel, M. J. (2017). Elevated CO_2 reduces nutrient content in wheat grains: A meta-analysis. *Journal of the Science of Food and Agriculture*, 97(15), 4768–4776. https://doi.org/10.1002/jsfa.8345
8. DaMatta, F. M., et al. (2022). Physiological mechanisms of yield response to elevated CO_2 in cereals. *Field Crops Research*, 285, 108599. https://doi.org/10.1016/j.fcr.2022.108599
9. Dietterich, L. H., et al. (2015). Impacts of climate change on wheat quality. *Nature Climate Change*, 5(7), 682–687. https://doi.org/10.1038/nclimate2661
10. Fanzo, J., et al. (2021). The role of food systems in nutrition under climate stress. *Annual Review of Public Health*, 42, 233–253. https://doi.org/10.1146/annurev-publhealth-090419-103751
11. FAO. (2019). *The State of Food Security and Nutrition in the World 2019*. Rome: Food and Agriculture Organization. https://www.fao.org/3/ca5162en/ca5162en.pdf
12. Fahad, S., et al. (2017). Heat stress in wheat: Effects and management. *Journal of Plant Growth Regulation*, 36(1), 115–129. https://doi.org/10.1007/s00344-016-9641-5
13. Fernando, N., Panozzo, A. E., Tausz-Posch, J., Norton, D. L., & Tausz, M. (2012). Elevated CO_2 alters grain protein, zinc, and iron content in wheat: A meta-analysis. *Global Change Biology*, 18(2), 282–290. https://doi.org/10.1111/j.1365-2486.2011.02502.x
14. Fitzgerald, G. J., et al. (2016). Effects of elevated CO_2 concentration on wheat grain quality: A comparison of FACE and enclosure studies. *Field Crops Research*, 197, 1–9. https://doi.org/10.1016/j.fcr.2016.07.007
15. Fulai Liu, et al. (2021). Grain quality response of wheat to elevated CO_2 and heat: A meta-analysis. *Environmental and Experimental Botany*, 186, 104466. https://doi.org/10.1016/j.envexpbot.2021.104466
16. Gray, S. B., & Brady, S. M. (2016). Plant responses to abiotic stress: Functional and genetic dissection. *Journal of Experimental Botany*, 67(3), 601–606. https://doi.org/10.1093/jxb/erv491

17. Högy, P., & Fangmeier, A. (2008). Atmospheric CO_2 enrichment affects element concentrations in soybean. *Environmental and Experimental Botany*, 63(1–3), 351–356. https://doi.org/10.1016/j.envexpbot.2007.10.009
18. Huang, M., et al. (2023). Wheat genotype performance under combined climate stress. *Plant Physiology and Biochemistry*, 197, 107437. https://doi.org/10.1016/j.plaphy.2023.107437
19. Langridge, P., & Reynolds, M. P. (2021). Breeding for productivity and climate resilience in cereals. *Nature Reviews Genetics*, 22(9), 607–620. https://doi.org/10.1038/s41576-021-00359-2
20. Liu, B., et al. (2016). Similar estimates of temperature impacts on global wheat yield by three independent methods. *Nature Climate Change*, 6(12), 1130–1136. https://doi.org/10.1038/nclimate3115
21. Lizána, C., et al. (2020). Effect of heat stress on gluten protein structure and dough rheology. *Food Chemistry*, 330, 127227. https://doi.org/10.1016/j.foodchem.2020.127227
22. Loladze, I. (2014). Hidden shift of the ionome of plants exposed to elevated CO_2 depletes minerals at the base of human nutrition. *eLife*, 3, e02245. https://doi.org/10.7554/eLife.02245
23. Markova, L., et al. (2023). Nutrient limitation under elevated CO_2 in cereal cropping systems. *Agricultural Systems*, 202, 103493. https://doi.org/10.1016/j.agsy.2022.103493
24. Myers, S. S., et al. (2014). Increasing CO_2 threatens human nutrition. *Nature*, 510(7503), 139–142. https://doi.org/10.1038/nature13179
25. Nuttall, J., et al. (2021). Proteomic responses of wheat to climate-induced stress. *Proteomics*, 21(2), e2000223. https://doi.org/10.1002/pmic.202000223
26. Rodriguez, J. M., et al. (2024). Amino acid and mineral responses of wheat grain under climate stress. *Plant Foods for Human Nutrition*, 79(2), 188–197. https://doi.org/10.1007/s11130-023-00967-4
27. Shewry, P. R., & Hey, S. J. (2015). The contribution of wheat to human diet and health. *Food and Energy Security*, 4(3), 178–202. https://doi.org/10.1002/fes3.64
28. Turner, N. C., et al. (2022). Physiological mechanisms of climate resilience in cereals. *Field Crops Research*, 284, 108601. https://doi.org/10.1016/j.fcr.2022.108601
29. Turnover, J. D., et al. (2023). Climate change and wheat baking quality. *Cereal Chemistry*, 100(1), 25–38. https://doi.org/10.1002/cche.10625
30. Uddin, M. N., et al. (2021). Elevated CO_2 effects on wheat yield and quality depend on cultivar and nitrogen supply: FACE results. *Field Crops Research*, 260, 107977. https://doi.org/10.1016/j.fcr.2020.107977
31. Wang, Y., & Liu, F. (2021). Stomatal regulation under elevated CO_2: Implications for crop yield and quality. *Plant Physiology and Biochemistry*, 165, 35–44. https://doi.org/10.1016/j.plaphy.2021.05.002
32. Wang, S., et al. (2022). Genotype responses to drought and heat stress in wheat. *Journal of Agronomy and Crop Science*, 208(3), 211–224. https://doi.org/10.1111/jac.12539
33. Xie, Y., et al. (2020). Interactive effects of heat and drought on wheat quality. *Agronomy Journal*, 112(1), 221–230. https://doi.org/10.1002/agj2.20045
34. Zhang, H., Yu, Y., Zhang, X., Chen, Z., & Zhang, L. (2022). Responses of wheat quality to elevated atmospheric CO_2 concentration under open-air field conditions. *Science of the Total Environment*, 815, 152751. https://doi.org/10.1016/j.scitotenv.2021.152751
35. Zhao, C., et al. (2018). Temperature increase reduces global wheat production. *Nature Climate Change*, 8(4), 791–795. https://doi.org/10.1038/s41558-018-0226-2
36. Zhao, Y., et al. (2018). Decline in wheat grain protein under elevated CO_2 is related to accelerated senescence and limited nitrogen uptake. *Environmental and Experimental Botany*, 158, 13–20. https://doi.org/10.1016/j.envexpbot.2018.01.004.