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A case for breeding heat-tolerant broccoli

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Poor farming and human nutrition cost lives and $10 trillion/yr. Broccoli is rich in phytochemicals implicated in reduced morbidity, but maladapted to the tropics and subtropics, where human illness is severe. Here we review advances in biology and breeding to propose a blueprint for a global broccoli breeding program— designed to improve adaptation to high heat environments, harness its current health benefits, and reduce impacts of long carbon-intensive supply chains.

A strategy to manage the global nutrition and health crisis

The global food and healthcare systems face unprecedented challenges that demand innovative solutions. The crisis is multidimensional, and many tactics will be needed to manage it, including increasing the availability, access, and adoption/consumption of healthy foods. The societal, environmental, and medical costs associated with current agricultural systems and poor dietary and health habits amount to $10 trillion annually[1]. Central to this crisis is the "Triple Burden" of malnutrition: undernutrition, micronutrient deficiencies, and overweight/obesity, which affect both developed and developing nations[1]. According to the World Health Organization (WHO) and the Food and Agriculture Organization (FAO) guidelines, a minimum intake of 400 g of fruits and vegetables per day is necessary for optimal health[2]. However, dietary patterns worldwide often fall short of this target, with global vegetable intake estimated at just 186 g per day[3–7]. This issue is evident even in countries with abundant food supplies. For instance, in the United States, the paradox of food abundance alongside widespread nutritional deficiencies is striking—fewer than 10% of Americans meet the USDA's recommended daily vegetable intake of 3 cups[8]. Meanwhile, rapid population growth and urbanization continue to amplify the demand for sustainable and reliable food sources, straining production and distribution chains.

Addressing these challenges requires systems approaches that encourage dietary shifts toward nutrient-dense foods and leverage agricultural innovations to bolster sustainability. Cruciferous vegetables are nutrient-dense crops[9]. Broccoli is a nutritional powerhouse, rich in essential vitamins such as A, C, K1, and folate, along with iron, zinc, and other minerals[9]. Folate is particularly important during pregnancy for fetal development[10]. Beyond its vitamin and mineral content, broccoli contains an array of bioactive compounds with significant health benefits. Its flavonoids have potent antioxidant[11,12] and anti-inflammatory properties[13,14], helping to lower the risk of chronic diseases, including cardiovascular conditions and certain cancers[15–17]. Additionally, broccoli is abundant in glucosinolates[18]—plant compounds that break down into bioactive isothiocyanates, known for their antioxidant and anti-cancer effects[19,20]. Variants like purple broccoli contribute further benefits due to their high levels of anthocyanins[21], which provide additional anti-inflammatory, antidiabetic, and anti-cancer properties[22]. While pungent flavors may hamper consumption, we foresee broccoli as an important dietary component to reduce nutrient deficiencies and chronic disease.

In contrast to root and cereal breeding supported by the Consultative Group on International Agricultural Research (CGIAR)[23], a center for global crop improvement and strategy for fruits and vegetables —broccoli in particular—remains lacking. Here, we review available tools, recent advances, and future directions to build a global broccoli breeding program aimed at increasing the sustainable production of this nutrient-rich crop. This review is structured around three core objectives:

I. Define the target population of environments for breeding and priority human communities.
II. Design a globally relevant breeding program that expands broccoli's area of adaptation, enabling more communities to benefit from its health-promoting properties, while also outlining research needs to accelerate genetic gain for nutrient density.
III. Define a framework to translate increased availability via improved cultivars into equitable access and widespread adoption.

Vulnerable and carbon-intensive supply chains

Current horticultural production presents critical economic, environmental, and logistical challenges. Much of the world's vegetable supply relies heavily on production in India, China, Mexico, and the United States, creating risks to global food security[24]. Centralization in productive areas increases resource use efficiencies[25,26] from the transformation of nutrients to economic resources via the vertical integration of production, processing, and distribution. However, centralization raises concerns about resilience and environmental sustainability[27], and food safety standards[28]. Concentrated production, and thus fertilizer and pesticide use, makes it difficult to manage externalities and disease outbreaks[29]. The economic and nutritional dependence of tropical and subtropical communities on vegetable production in temperate countries is also a cause for concern[30]. Similarly, in the United States, California's climate and resources have supported large-scale vegetable cultivation. Production scale supported a very efficient industry. However, this centralization has resulted in a brittle system[31]. Factors such as water scarcity[32], rising temperatures[33], increased number of fire events, and energy costs[34] make California's agricultural output highly vulnerable, raising questions about its resilience in the medium to long term.

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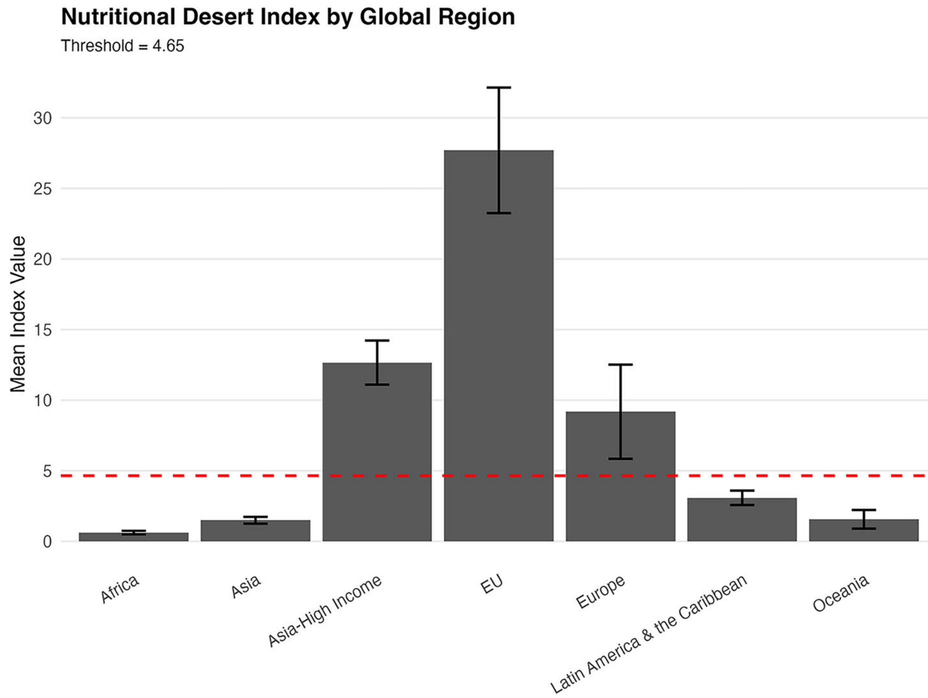

Fig. 1 | The Nutritional Desert Index was calculated as the ratio of GDP per capita to the distance from each country to its nearest major broccoli-exporting country. Values are summarized as regional means with standard errors. The red dashed line indicates a threshold, calculated as the maximum mean index among Africa, Asia, Oceania, and Latin America & the Caribbean—regions considered most vulnerable to nutritional insecurity. North America was excluded from the analysis due to a small sample size ($n = 2$). Asia–High Income includes Japan, South Korea, Kuwait, Qatar, Saudi Arabia, Singapore, United Arab Emirates, and Israel, classified as high-income economies by the World Bank. EU denotes for the European Union. Data were accessed through the World Bank (supplementary data Table 1). The threshold 4.65 is the mean index for Latin America and the Caribbean, plus 3.09 standard errors for the mean.

Transporting fresh produce thousands of miles—from temperate regions to the tropics and subtropics, and from western to eastern states in the U.S. and beyond—results in significant and inefficient energy use[34], greenhouse gas emissions, logistical complexity, and the emergence of nutritional deserts[35]. At the global scale nutritional deserts refer to all geographies where the ratio between the gross domestic product per capita and the distance to main production of area of broccoli is less than 4.65 (Fig. 1). This is a data driven threshold that effectively describes trade patterns and the concentration of trade in North America, and the European Union and Asia affluent countries (Fig. 2). Deserts are most evident in South America and Africa (Fig. 2), where broccoli is not widely produced, despite these being regions where increased consumption of fruits, vegetables, and broccoli could have the greatest nutritional impact. The perishability of vegetables further exacerbates food waste[36,37], reflecting broader global trends. In addition, long supply chains degrade the nutritional value of vegetables[38], as prolonged storage and transportation reduce their quality[39]. These challenges underscore the urgent need to implement more distributed agricultural models that can enhance sustainability, reduce carbon emissions, and ensure a stable, regionally distributed, and more equitable vegetable supply. One viable solution is highlighted by a Life Cycle Assessment (LCA) study of UK broccoli production, which demonstrates its remarkably low environmental impact due to efficient land and water use[40].

Tropical and subtropical socioeconomics

The greatest population growth and urban development are expected to occur in the tropics and subtropics, where the world's most vulnerable populations reside[41] and mortality rates are highest (Table 1). Developing distributed food production systems—particularly for vegetables like broccoli—in these regions could significantly benefit local communities by creating jobs and reducing mortality and morbidity. Regional and peri-urban food systems stimulate economies by generating employment in farming, distribution, marketing, and sales, while also providing consumers with fresher, more nutritious, and often more-affordable produce[42]. A clear example of this impact can be seen in the U.S. State of Florida, where nearly 32 jobs are created for every $1 million in revenue generated by produce farms engaged in direct marketing, compared to only 10.5 jobs for farms focused on wholesale distribution[43].

At the same time, the global broccoli market is experiencing strong growth, driven in part by increasing consumer preference for healthier diets. Valued at $5.5 billion in 2023, the market is projected to reach $9.5 billion by 2030, reflecting a compound annual growth rate (CAGR) of 7.2%[44]. This expanding demand presents an opportunity for regions around the world to invest in local production, strengthen food security, and eliminate nutritional deserts (Fig. 2). Additionally, consumer education and targeted investments can further increase the consumption of fresh fruits and vegetables, driving both health and economic benefits.

The case for a broccoli breeding program

Plant breeding has been a primary driver of yield improvements across crops and regions globally. While periodic yield plateaus have occurred, the ability to breed for both qualitative and quantitative traits remains firmly supported by the well-established principles of genetic variation and selection. The Green Revolution is a prime example of the transformative power of plant breeding[23]. By enabling agronomic intensification, plant breeding successfully prevented widespread food insecurity by increasing caloric availability across environments. However, this success came with unintended consequences, including declines in the nutritional quality of staple crops[45] and reduced resilience[46]. For example, breeding for higher-yielding wheat varieties and maize hybrids has led to reductions in protein content[47,48], and increasing fruit size in tomatoes and strawberries has been associated with declines in vitamin C, anthocyanins, and antioxidants[49,50]. Today, a new revolution is required—one that not only enhances the productivity, resilience, and adaptability of crops but also improves their nutritional value to address global health challenges.

Broccoli represents an ideal model crop for developing blueprints to accelerate genetic gain in nutritional content, resilience, and societal value—including applications in education—for fruit, vegetable, and row crop breeding. In addition to its naturally high and genetic variation for phytochemicals associated with human health, broccoli breeding is well-suited to a range of advanced technologies. These include molecular markers[51,52], dynamic modeling[53,54], doubled haploids[55,56], high-throughput imaging for nutritional and morphological traits[57], callus-stage selection, gene editing, breeding with gene editing approaches, and male sterility systems for hybrid development. Broccoli's relatedness to *Arabidopsis thaliana* offers an exceptional opportunity to leverage a well-established knowledge base to

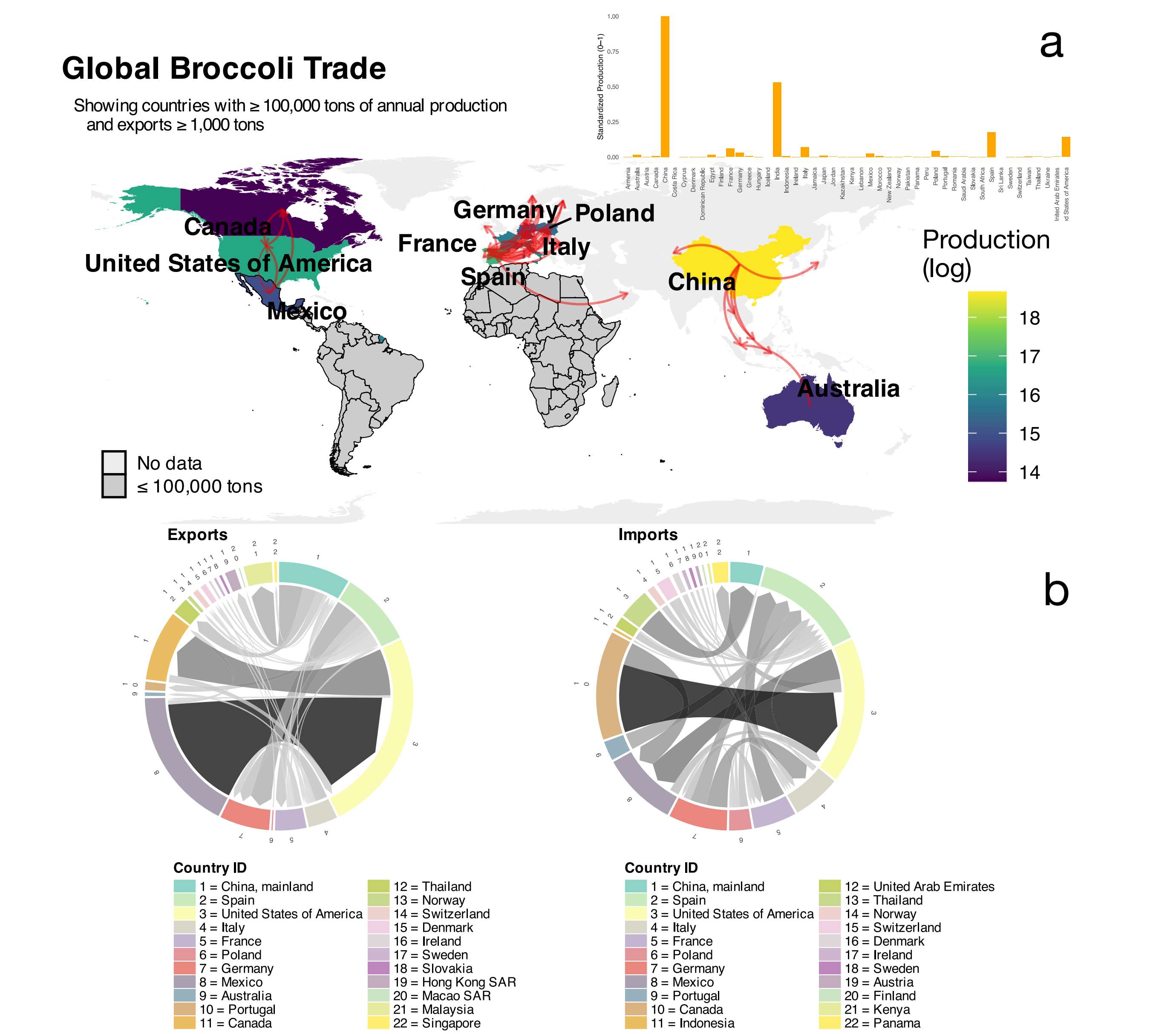

Fig. 2 | Global broccoli and cauliflower trade overview. a Countries producing ≥100,000 tons annually and exporting ≥1000 tons are highlighted. Arrows represent major export routes, with direction indicating trade flow. The bar chart on the right displays standardized total production across all reporting countries. **b** Chord diagrams illustrate the direction and volume of trade. The left panel shows exports, and the right panel shows imports. Arrows point toward the destination country, and their thickness corresponds to the quantity traded. Countries are labeled by numeric ID, with names listed below each diagram. Data sourced from FAO[106].

Table 1 | Summary of population growth, disease mortality, and vegetable consumption by climate zone

Climate zone	Population growth rate (%)[103]	Disease[a] type	Age-standardized mortality rate per 100,000[104]	Grams per day consumption of non-starchy vegetables[105]
Temperate	−0.06	Infectious	1.8	157
		Non-Infectious	29.3	
Subtropical	0.88	Infectious Diseases	6.1	154
		Non-Infectious Diseases	35.8	
Tropical	1.46	Infectious Diseases	19.5	150
		Non-Infectious Diseases	42.0	

[a]Infectious diseases included are malaria, dengue, lower respiratory infections, HIV/AIDS, drug-susceptible tuberculosis, diarrheal diseases, tuberculosis, measles, and meningitis. Non-Infectious Diseases encompass ischemic heart diseases, ischemic stroke, hypertensive heart disease, diabetes mellitus types 1 and 2, asthma, chronic obstructive pulmonary disease, cardiovascular diseases, atrial fibrillation and flutter, and intracerebral hemorrhage.

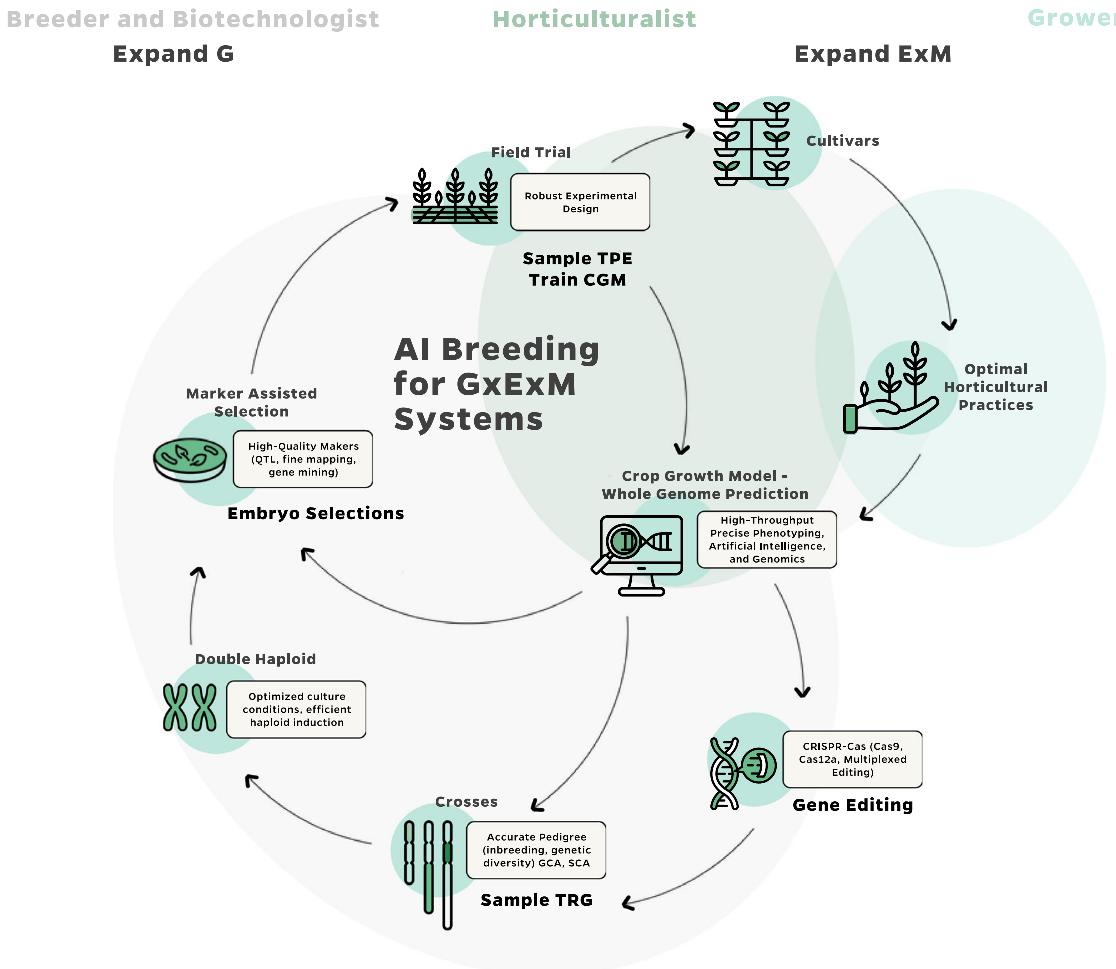

Fig. 3 | Conceptual pipeline for an AI-enabled broccoli breeding program, integrating predictive analytics, crop growth models, DH technology, marker-assisted selection at embryonic stages, high-throughput phenomics, and field trials to efficiently address complex traits such as heat tolerance and nutritional content. Expansion of the genetic space through directed sampling of the target reference genotypes and biotechnology, along with the expansion of environment × management spaces, is achieved by assimilating data from growers' fields.

improve germplasm with existing levels of heat tolerance[58], enabling the development of varieties suited to nutritional deserts, particularly in tropical and subtropical climates (Fig. 2).

Emerging technologies for crop improvement

An effective breeding program leverages emerging technologies to adequately sample the target reference of genotypes carrying desirable founder haplotypes and evaluate them within a representative sample of the target population of environments. Figure 3 outlines a conceptual pipeline for AI-enabled broccoli breeding that integrates predictive modeling, genomics, biotechnology, and high-throughput phenotyping. The pipeline begins with efficient experimental designs—such as sparse testing[59] —and managed environments designed to uncover genetic variation for traits of interest[60]. These experiments generate the data needed to train Artificial Intelligence (AI) models, enabling genotype (G) selection decisions based on predicted performance across the diverse environmental and management (M) conditions that characterize the target population of environments, including G × M interactions[60]. Among the many forms AI can take, the models that have proven effective at accelerating genetic gain[60] fall within the domains of statistical learning, optimization, and dynamical systems modeling[61]. On-farm data further enhance model training by expanding the G × M sample space. Prediction becomes central to selecting parent crosses[60], thereby expanding exploration of the G space. The efficiency of the breeding program depends on accurate AI models, streamlined processes for seed or propagule production, rapid development of uniform materials such as doubled haploids for genetic evaluation, the use of high-quality phenomics data, and predictive tools capable of discarding inferior genotypes—ideally at early stages such as callus development. In addition, transgenic, gene editing, and synthetic biology technologies expand the accessible genetic space by introducing novel variation beyond what exists in the germplasm of interest[60,62].

The incorporation of high-throughput phenotypic, environmental, and genomic data has significantly improved trait selection and crop performance modeling[63]. Predictive breeding lies at the core of breeding program efficiency and effectiveness (Fig. 3). Using the breeder's equation[60], it can be shown that the rate of genetic gain is directly proportional to the increase in prediction accuracy (r_a) between phenotypic measurements in experimental trials and the underlying true breeding values. The most advanced approaches improve r_a by leveraging ensembles of models to capture complex genetic networks influencing trait expression[61,64], incorporate environmental covariates[65], and fuse dynamic systems models with Bayesian algorithms to model the interdependent relationships among G, E, M, and temporal physiological processes[60,66]. These dynamic models are grounded in principles of resource capture, use, and allocation, helping prevent overfitting and "model hallucinations" while improving prediction rigor.

A crop model is a selection index because it integrates genomic and environmental predictors to estimate breeding values for multiple traits

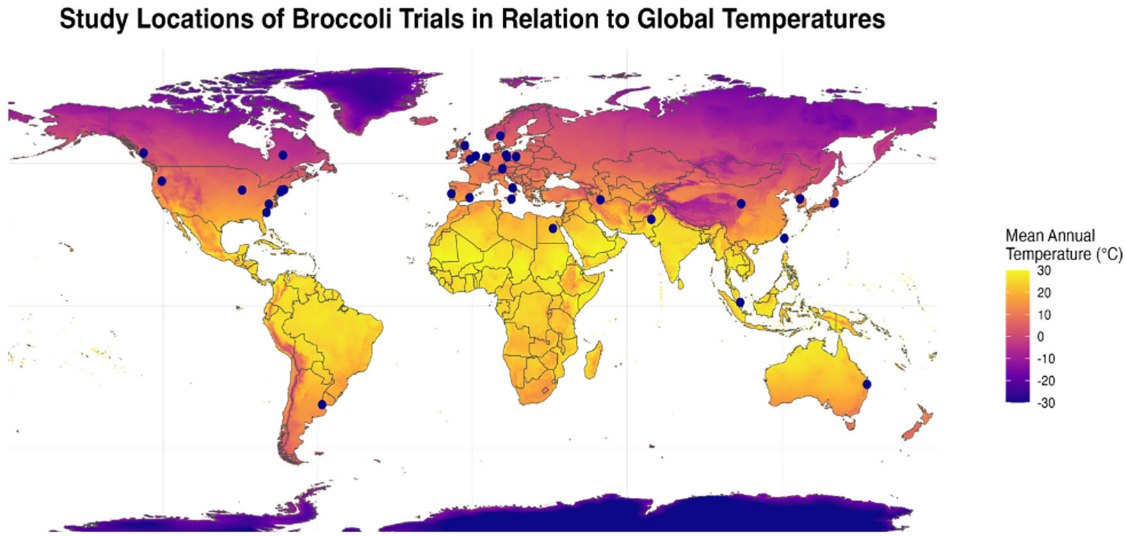

Fig. 4 | Geographical distribution of broccoli trial study locations (blue dots), compiled using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines[107], overlaid on a global map of mean annual temperature (°C). The map shows that most studies are concentrated in temperate regions, with limited research conducted in tropical and subtropical climates. Search terms included: "*Brassica oleracea* var. *italica*," "broccoli," "temperature," "photoperiod," "nitrogen," "heat," "crop growth model," "photosynthesis," "leaf appearance rate," "leaf area," "inflorescence," and "quantitative trait loci (QTL)".

across the target population of environments[67,68]. It improves r_a by identifying key traits that contribute the most to genetic gain for the target environmental conditions. It simulates adaptation considering time to flowering, leaf area development, photosynthesis, and other interconnected traits. These dependencies implicitly define trait weights that influence the outcomes—such as yield and nutritional quality—on which breeders base selection decisions. Trait dependencies could be represented in a matrix form, illustrating the multivariate nature of this selection index[61]. Using a crop model as a selection index enables a dynamic approach in which trait weights vary over time and cycles of selection. In the case of broccoli, a crop model will likely weigh time to flowering first to expand the area of adaptation (see role of *FLC* on heat tolerance below), second, photosynthesis and leaf area development to increase productivity and energy available to produce energy-dense phytochemicals, and finally, production of secondary metabolites to increase nutrient concentrations.

Recent advances in large language models have further accelerated genome and protein sequence predictions[69]. Deep learning approaches, such as AlphaFold, have dramatically improved protein structure modeling and facilitated the rational design of sequences and proteins for synthetic biology and biotechnology applications[70]. Modern gene-editing tools now allow for simultaneous and highly precise modification of multiple genes[71,72]. These systems support non-integrative genome modifications using RNA virus-based vectors for delivery into plant tissues, resulting in heritable modifications and virus-free mutated progeny[73–76]. Gene editing offers breeders precise, targeted methods to enhance traits such as disease resistance, environmental adaptability, nutritional content, and production of hybrids. Successful interventions have improved glucosinolate production via *MYB* transcription factors[77,78], boosted flavonoid biosynthesis[79], and optimized pathways for vitamin C[80], omega-3 fatty acids[81,82], and anthocyanin accumulation[83]. Targeted editing of *ORF138* has been shown to restore cytoplasmic male sterility[84], enabling hybrid seed production. The ability to simultaneously edit multiple loci opens new avenues for developing resilient, broadly adapted, and nutritionally enhanced broccoli varieties[71]. The relationship between *Arabidopsis thaliana* and broccoli allows researchers to harness extensive genomic annotations and functional knowledge, improving the efficiency of gene editing and metabolic engineering in broccoli compared to more distantly related species. In breeding programs, doubled haploid lines provide genetic uniformity and are used as cultivars or parental lines for F1 hybrid development. In broccoli, these can be produced through anther or microspore culture[85,86], enabling selection at the callus stage. Together with other advanced breeding tools, breeders can develop hybrids or self-pollinated lines that combine robust environmental adaptability with desirable consumer traits such as flavor, texture, and market appeal[87].

Brassica oleracea is understudied in tropical and subtropical environments

Breeding technologies capable of doubling the rate of genetic gain—as demonstrated in drought-tolerant maize programs[60,66]—depend on a deep biological understanding of crop improvement. Although dynamic models have been proposed for broccoli[53], the crop remains significantly underrepresented in research targeting adaptation to tropical and subtropical environments (Fig. 4). A systematic review conducted using the PRISMA flowchart methodology identified 1581 articles, of which only 48 addressed key topics such as heat tolerance, tropical and subtropical adaptation, physiology, modeling, or genetics (Supplementary Table 2). These studies consistently highlight temperature as a critical factor influencing broccoli development, yield, and head quality, with both heat and cold extremes impairing growth[88–92]. The striking overlap between regions characterized by nutritional deserts and long supply chains (Fig. 2) and the lack of research studies in these same areas (Fig. 4) underscores a fundamental knowledge gap that must be urgently addressed.

Optimal head initiation and yield in broccoli occur between 16–18 °C, while temperatures exceeding 30 °C arrest inflorescence development, resulting in uneven or absent heads[89,90,93]. In contrast, cooler temperatures around 12 °C delay vegetative growth and induce earlier bud formation at a younger morphological stage[94]. Temperature-dependent linear models have been developed for head initiation and growth in the 0–17 °C range[95]. However, under subtropical conditions, broccoli may flower more rapidly when exposed to longer photoperiods and higher temperatures[96]. Although genomic research on broccoli flowering under tropical and subtropical conditions remains limited, upregulation of *BoFLC1* has been consistently observed in heat-sensitive broccoli genotypes, while promoter variation in *BoFLC1* has been identified as a potential genetic factor distinguishing heat-tolerant from heat-sensitive broccoli lines[97]. In cauliflower (*Brassica oleracea* var. *botrytis*), *BoFLC1* downregulation has been associated with curd development at temperatures of 26–30 °C[98]. In cabbage (*Brassica oleracea* var. *capitata*), expression of tandemly duplicated *BoFLC1* genes (*BoFLC1a* and *BoFLC1b*) has been implicated in the inhibition of flowering[99]. Heat tolerance in broccoli is polygenic, offering valuable insights for breeding resilient varieties able to thrive under high-temperature conditions (20–30 °C)[100]. Five major QTL associated with heat tolerance were identified in a doubled haploid mapping population evaluated under summer field conditions[52]. Two additional QTL, with heat tolerance significantly correlated with early flowering time[51]. These findings highlight the potential for marker-assisted selection to accelerate the development of heat-tolerant broccoli adapted to tropical and subtropical regions. While existing studies are constrained by limited genotype and environment testing, they collectively suggest that flowering time regulators and integrators of signal, such as *FLC*[101], play a central role in adaptation to the tropics and subtropics, with emerging evidence of trade-offs between early maturity and stress resilience that merit further exploration. Realizing the full potential of heat-resilient broccoli will require sustained investment and research across diverse germplasm evaluated under a broad range of environmental conditions. To achieve meaningful progress, a robust breeding framework is needed—one that draws from both established literature and emerging technologies.

Expanding availability, access, and adoption of heat-tolerant broccoli

To address the global nutritional crisis and generate broader societal value, breeding objectives must be reimagined to incorporate considerations of availability, access, and adoption. Availability must go beyond simply closing the yield gap in major producing regions (Fig. 2) to include nutritional quality, such as enhanced nutrient content. Access refers to the development of cultivars suited to a wide range of target environments—including the nutritional deserts of the world (Fig. 2, Table 1)—and the capacity for farmers to locally produce seeds or propagules. Adoption must consider the organoleptic and culinary properties of varieties to overcome cultural and socioeconomic barriers. G x M strategies can enhance resilience to biotic and abiotic stresses, thereby improving both the availability and accessibility of nutritious crops.

While global nutritional deserts are predominantly located in tropical and subtropical regions, this broad target population of environments represents a complex mix of abiotic and biotic conditions. These environments may require the development of cultivars with specific adaptations to ensure stable nutrient availability. Distributed breeding systems that facilitate the exchange of germplasm have proven to be among the most effective strategies for addressing the complexity of such a target population of environments[102]. Collaborative efforts among international institutions, local agricultural colleges, and regional research centers are essential for establishing breeding programs, sharing germplasm, and equipping breeders with the tools and knowledge needed to develop regionally adapted cultivars. Critically, educational programs aimed at empowering breeders to fully leverage both native and novel sources of variation are currently lacking—and are urgently needed to accelerate genetic gains in nutritional quality across crops.

Ensuring access to improved vegetable varieties also requires addressing the affordability and availability of seed. Most broccoli seed used globally originates from hybrid breeding programs, with production concentrated in regions such as California, India, China, and Mexico. In contrast, seed consumption spans a broader range of temperate locations, which further reinforces the lack of adapted germplasm for tropical and subtropical climates (Fig. 5). While hybrid varieties offer advantages in yield and uniformity, their high costs often make them inaccessible to smallholder farmers; thus, alternative seed systems are essential. Self-pollinated and open-pollinated broccoli would allow farmers to save seed. In addition to seed saving, broccoli can be propagated through vegetative cuttings—a practice that, while uncommon, offers a viable alternative for increasing plant availability where access to quality seed is limited. Clonal propagation, currently feasible in broccoli, would allow farmers to rapidly expand their plant stock without relying solely on commercial seed suppliers, facilitating the cultivation of this nutrient-dense crop in areas where affordability and distribution constraints hinder adoption. This approach could be particularly impactful in rural and low-income communities, where increasing access to nutritious vegetables like broccoli is critical for improving dietary diversity and public health.

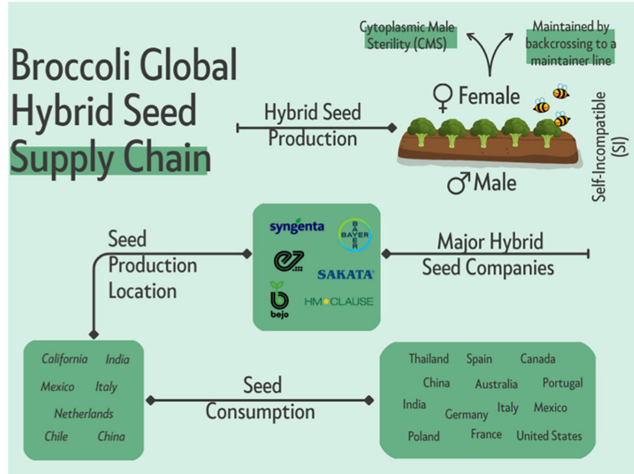

Fig. 5 | Global hybrid seed supply chain for broccoli. This diagram illustrates the major components of hybrid broccoli seed production, including the use of cytoplasmic male sterility and self-incompatibility systems for hybrid development. It highlights key commercial seed companies, the primary regions where hybrid seed is produced, and the broader global markets where seed is consumed. The geographic disconnect between seed production (concentrated in temperate regions) and the underrepresentation of adapted germplasm for tropical and subtropical environments underscores a critical gap in access. This supply chain structure limits the availability and affordability of suitable varieties for stallholder farmers in low-income regions.

Supporting the development and distribution of open-pollinated and self-pollinated varieties would help smallholder farmers achieve greater seed sovereignty and autonomy. It would help reduce dependency on commercial seed suppliers—especially in areas with limited market access and persistent nutritional deserts (Fig. 2)—and contribute to the long-term sustainability of vegetable production systems. However, broccoli cultivars that are truly adapted to tropical and subtropical environments remain largely unavailable. Varieties marketed in these nutritional deserts often rely on vague claims of heat tolerance, lacking clear temperature thresholds, supporting trial data, or specific definitions of the environmental conditions under which heat tolerance was evaluated. In nearly all cases, cultivars are still recommended for winter production in subtropical regions, and none are explicitly promoted for use in true tropical climates (Table 2). This gap is reflected in the low production levels across many tropical and subtropical regions (Fig. 2), despite the urgent need for nutritionally dense crops like broccoli in areas facing the highest rates of nutritional insecurity.

While improving access to heat-adapted cultivars is essential, it is only part of the challenge. Widespread adoption of heat-tolerant crops also depends on overcoming economic, cultural, and behavioral barriers. While technical innovation, policy support, and infrastructure are essential, securing farmer and consumer acceptance is equally critical. Public health campaigns, community-led cooking demonstrations, and school-based nutrition programs can familiarize consumers with the improved flavor and health benefits of these crops. By integrating education, policy, and targeted breeding efforts, heat-tolerant broccoli can serve as a model for future crop improvement initiatives that address climate resilience, food security, and public health in tandem. Expanding access to improved vegetable varieties requires a coordinated effort across breeding institutions, policymakers, and industry stakeholders to ensure that the benefits of agricultural innovation reach the farmers and communities who need them most. The development of heat-adapted broccoli would represent a scientific breakthrough as well as a broader shift toward sustainable, nutrition-driven breeding programs that strengthen food systems worldwide.

Table 2 | Commercially available crown-cut broccoli cultivars marketed as "heat-tolerant" by seed companies, along with their typical harvest periods

Seed company	Cultivar	Harvest period	Stated heat tolerance claim
Sakata Seed	Green Magic	December or March	"For summer harvest"
	Eastern Crown	October-November or January-March	"Performs well in long day length and moderate heat"
	Emerald Star	January-March	"Performs best in cool to warm and warm to cool seasons"
	Expo	January-February	"Performs well in warm to cool conditions"
	Green Gold	January-February	"Heat-tolerant"
	Gypsy	November-December	"Good heat tolerance"
	Imperial	February-March	"Performs well in long day length and moderate heat"
	Millennium	January-March	"Excellent heat tolerance"
	Emerald Crown	December or March	"Growing season is warm to cool (not for rainy season)"
Tainong Seed	Kings Crown	February-March	"Heat tolerance"
	Power Dome	December-February	"Heat tolerance for summer"
Bayer (Seminis)	Castle Dome	December or February	"Heat-loving hybrid"
	Hancock	February-March	"Very good heat tolerance"
	Lieutenant	November or February	"Impressive performer in Summer heat when well-watered"
	Ironman	December-January	"Heat resistant"
Harris Moran	Asteroid	February-March	"Good heat tolerance"
	Virgo	February-March	"Heat-tolerant"

Data availability
Data is provided within the manuscript or supplementary information files.

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Competing interests

The authors declare no competing interests.

Additional information

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