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Integrating Genotype, Environment, and Processing (G × E × P): A Farm-to-Food Framework for Climate-Resilient Rice Quality

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ABSTRACT

Climate change affects not only rice production but also grain quality and subsequent food-processing performance. Although genetic determinants, environmental stresses, and postharvest processing have been extensively investigated, their integration across the grain-to-food continuum remains limited. This review synthesizes evidence on how genotype (G) establishes grain-quality potential, how climate-related environmental conditions (E) particularly heat, drought, and salinity during grain development modify grain composition and structure, and how processing (P) further transforms these characteristics into final food-quality outcomes. Particular attention is given to starch structure, proteins, lipids, and bioactive compounds and their implications for processing behavior, texture, digestibility, resistant starch formation, and nutrient retention. Based on established and emerging relationships across these domains, we propose an evidence-informed Genotype × Environment × Processing (G × E × P) framework for understanding rice-quality resilience from grain development to consumption. The framework is presented as an empirically testable model rather than an established universal three-way interaction. Integrating grain-quality stability into breeding and processing strategies could support the development of rice cultivars and food products that maintain desirable technological and nutritional characteristics under increasingly variable climatic conditions.

Keywords: Rice Grain Quality; Genotype × Environment × Processing; Climate Resilience; Starch Functionality; Postharvest Processing; Food Quality

1. INTRODUCTION

Rice (*Oryza sativa* L.) is one of the world's most important staple crops and a major source of dietary energy, particularly across Asia, making it central to global food security (Fukagawa & Ziska, 2019). Climate-adaptation efforts in rice have traditionally emphasized maintaining productivity and improving tolerance to environmental stress (Sreenivasulu et al., 2015). However, yield resilience alone does not ensure the preservation of desirable grain-quality characteristics. Climate-related conditions during grain development can modify the biochemical and structural properties of rice, with consequences for its processing, cooking, and nutritional quality (Liu et al., 2025; Shi et al., 2017). Thus, climate resilience in rice should encompass not only stable production but also the capacity to maintain grain quality and subsequent food functionality under changing environmental conditions.

Rice grain quality is a complex phenotype governed by coordinated developmental and metabolic processes. Genes regulating starch biosynthesis, storage-protein accumulation, lipid metabolism, and secondary metabolite synthesis establish the intrinsic quality potential of a cultivar. Allelic variation in these genetic determinants contributes to differences in apparent amylose content (AAC), amylopectin fine structure, gelatinization temperature, pasting properties, cooked-grain texture, and nutritional composition (X. Wang et al., 2017). Advances in molecular marker technologies, quantitative trait locus (QTL) mapping, genome-wide association studies (GWAS), and genome editing have expanded opportunities to identify and target genetic determinants associated with grain-quality traits (Achary & Reddy, 2021). Nevertheless, genetic potential does not translate into a fixed grain-quality phenotype; its expression can be substantially modified by environmental conditions during grain development (Shi et al., 2017).

Climate-induced abiotic stresses are particularly consequential during reproductive development and grain filling, when the major structural and biochemical components of the rice grain are formed. Elevated temperatures can disrupt endosperm development, starch biosynthesis, and the deposition and organization of storage compounds, frequently increasing grain chalkiness and altering physicochemical quality (Fernando et al., 2025; Shi et al., 2017). Water deficit can restrict photo assimilate availability and disrupt assimilate translocation and grain-filling dynamics, whereas salinity can interfere with ion homeostasis, osmotic balance, and metabolic processes involved in grain development (Fernando et al., 2025). These stresses can consequently modify grain appearance, starch structure and composition, protein accumulation, and other quality-related characteristics. Importantly, the magnitude and direction of these responses vary among rice genotypes, demonstrating that grain quality is shaped by genotype × environment (G × E) interactions rather than by genotype or environment independently (Shi et al., 2017).

The quality experienced by consumers is ultimately determined after postharvest processing and food preparation. Operations such as milling, parboiling, cooking and cooling, germination, and fermentation can substantially modify the physical structure and chemical composition of rice. Milling removes the bran and germ fractions and consequently reduces several nutrient-rich components of the grain (Tong et al., 2019). Hydrothermal treatments, including parboiling and cooking, induce starch gelatinization and structural reorganization, while subsequent cooling promotes starch retrogradation and can increase resistant starch (RS) formation (Boers et al., 2015). Germination and fermentation further modify grain composition through endogenous enzymatic and microbial activity and may enhance the availability or concentration of selected bioactive and nutritional components (Chinma et al., 2024). Importantly, processing outcomes depend partly on the physicochemical characteristics of the raw grain; differences in starch composition, grain structure, and nutritional composition can therefore influence responses to processing (Atungulu & Pan, 2014). This dependence provides a mechanistic basis for considering genotype × processing (G × P) and environment × processing (E × P) relationships when evaluating final rice food quality.

Despite substantial advances in agronomy, cereal chemistry, and food science, the determinants of rice quality are commonly investigated at different stages of the grain-to-food continuum. Agronomic studies have primarily examined how genotype and environmental conditions influence grain development and harvested quality traits (Shi et al., 2017; Sreenivasulu et al., 2015), whereas food-processing studies have focused largely on how milling, hydrothermal treatment, cooking, germination, fermentation, and related operations modify grain composition and functionality (Atungulu & Pan, 2014; Chinma et al., 2024). Consequently, the effects of genotype (G), environment (E), and processing (P) are often considered separately or through pairwise relationships, while their integration across the complete grain-to-food pathway remains comparatively underdeveloped. This fragmentation limits understanding of how environmentally modified grain phenotypes subsequently respond to processing and ultimately determine food quality.

This review therefore integrates preharvest genetic and environmental determinants of rice quality with postharvest processing and food functionality. We propose a Genotype × Environment × Processing (G × E × P) framework to conceptualize how genetic potential, environmental conditions during grain development, and subsequent processing collectively shape the final food phenotype. Rather than treating the three-way interaction as an established universal effect, the framework is presented as an evidence-informed and empirically testable model that connects established pairwise relationships across the grain-to-food continuum. The review synthesizes the molecular and physicochemical mechanisms linking preharvest conditions with postharvest functionality, identifies critical knowledge gaps, and outlines integrated breeding and processing strategies for developing rice with greater quality stability under climate variability.

2. METHODOLOGY

This review employed a structured narrative review and conceptual synthesis approach to integrate evidence from plant molecular biology, crop physiology, cereal chemistry, and food processing. Relevant peer-reviewed literature was identified through searches of Web of Science Core Collection and Scopus. These multidisciplinary databases were selected to provide broad coverage of research spanning rice genetics, environmental stress responses, grain chemistry, processing, and food-quality characteristics. The retrieved literature was synthesized to examine established relationships among genotype, environmental conditions, grain composition, processing responses, and final food quality, and to provide the evidence base for the proposed Genotype × Environment × Processing (G × E × P) framework.

2.1 Search Strategy and Keyword Matrix

Search terms were organized into three thematic clusters corresponding to the major components of the proposed G × E × P framework:

- Genotype (G): "rice," "*Oryza sativa*," "genotype," "cultivar," "grain quality," "starch biosynthesis," "amylose," "amylopectin," "starch structure," "storage protein," "QTL," "GWAS," and "genome editing."
- Environment (E): "heat stress," "high temperature," "drought," "water deficit," "salinity," "salt stress," "climate change," "grain filling," "grain development," and "chalkiness."
- Processing (P): "milling," "parboiling," "cooking," "cooling," "retrogradation," "resistant starch," "germination," "fermentation," "digestibility," "pasting properties," and "food quality."

Keywords within and across these clusters were combined using Boolean operators (AND/OR) in Web of Science Core Collection and Scopus. Searches were structured to identify evidence concerning individual components as well as relationships across the grain-to-food continuum. Representative combinations included G × E ("rice genotype" AND "heat stress" AND "grain quality"), G × P ("rice cultivar" AND "processing" AND "starch digestibility"), and E × P ("grain filling temperature" AND "rice" AND "cooking quality"). Additional combinations incorporating terms from all three clusters were used to identify studies potentially linking genotype, environmental conditions, and processing outcomes.

2.2 Inclusion and Exclusion Criteria

Studies were considered eligible when they provided evidence relevant to rice grain quality across one or more components of the proposed G × E × P framework. Primary peer-reviewed empirical studies examining grain composition, starch structure, physicochemical properties, processing behavior, cooking quality, digestibility, or nutritional characteristics were included. Studies investigating the effects of genotype, climate-related environmental stresses, or postharvest processing on these characteristics were prioritized. Meta-analyses and review articles were additionally consulted where they provided relevant mechanistic context or synthesis of established evidence.

Studies were excluded when they focused exclusively on vegetative growth, yield, or agronomic stress tolerance without evaluating grain-quality or food-functionality outcomes. Studies involving non-rice matrices, articles lacking relevance to the grain-to-food continuum, and non-peer-reviewed publications were also excluded.

2.3 Study Selection and Evidence Synthesis

Titles and abstracts retrieved from Web of Science Core Collection and Scopus were screened for relevance to rice grain quality and food functionality. Potentially relevant publications were subsequently evaluated in full text. Evidence was organized according to the principal relationships represented within the proposed framework, including G × E, G × P, and E × P, as well as studies providing evidence potentially relevant to integration across all three domains. For each study, attention was given to the genotype or genetic determinant investigated, environmental treatment or growing condition, grain-quality characteristics, processing operation, and resulting physicochemical, nutritional, or food-functional outcomes. The evidence was then synthesized across the continuum:

Genotype (G) → Environment (E) → Harvested Grain Phenotype → Processing (P) → Final Food Quality

Importantly, studies demonstrating individual or pairwise relationships were distinguished from evidence directly evaluating combined effects across genotype, environment, and processing. This distinction was used to establish the evidence base for the proposed G × E × P framework without assuming that a universal three-way interaction has already been experimentally demonstrated.

2.4 Evidence Assessment and Qualitative Classification

The strength and relevance of the included evidence were evaluated qualitatively according to study design, experimental control, and the directness of the relationships examined. Controlled studies specifying rice genotype, environmental treatment, and/or processing conditions were considered particularly informative for identifying mechanistic relationships, whereas multi-environment field studies were used primarily to evaluate the consistency and environmental stability of genotype-dependent grain-quality responses.

Evidence was further classified according to the degree of integration across the proposed framework. Direct evidence referred to studies in which multiple components of the genotype–environment–processing continuum were evaluated within the same experimental design. Indirect evidence referred to relationships supported by complementary findings from separate studies that could be mechanistically linked across disciplines. Particular attention was given to distinguishing established G × E, G × P, and E × P relationships from evidence relevant to the proposed G × E × P framework. A three-way G × E × P interaction was considered experimentally demonstrated only where genotype, environment, and processing were jointly evaluated within an appropriate factorial or interaction-based analytical design.

3. LITERATURE REVIEW

3.1 Genetic and Molecular Determinants of Rice Grain Quality

The intrinsic quality potential of rice is established during grain development through genetic regulation of starch, storage proteins, lipids, and bioactive compounds. Starch is the predominant component of the rice endosperm and a major determinant of cooking, textural, pasting, and digestibility characteristics. Its functional properties depend largely on the relative abundance and molecular organization of amylose and amylopectin, which vary considerably among rice genotypes (X. Wang et al., 2017).

Several key genes regulate these starch characteristics. The *Waxy (Wx)* gene, encoding granule-bound starch synthase I (GBSSI), is a major determinant of apparent amylose content (AAC), with consequences for cooked-grain texture and retrogradation. Amylopectin structure is controlled by coordinated activities of starch synthases, branching enzymes, and debranching enzymes. In particular, *SSIIa/ALK* influences amylopectin chain structure and gelatinization properties (Waters et al., 2006), while *SBEIIb* contributes to branch architecture and starch digestibility (Butardo et al., 2011). Regulatory genes such as *OsbZIP58* and *FLO2* further influence starch accumulation and endosperm development (She et al., 2010).

Genetic variation also influences storage proteins, lipids, pigments, and other bioactive constituents that contribute to nutritional and processing quality. These components interact with starch and grain structure to affect hydration, gelatinization, texture, digestibility, and nutrient retention. Advances in molecular breeding and genome editing provide opportunities to target such quality traits, as demonstrated by modification of *GW2* and associated changes in grain and nutritional characteristics (Achary & Reddy, 2021). However, these genetically determined characteristics represent quality potential rather than a fixed final phenotype, because their expression is subsequently modified by environmental conditions during grain development. Key genetic and molecular determinants of rice grain quality and their principal functional consequences are summarized in Table 1.

Table 1. Key Genetic Determinants of Rice Grain Quality

Key gene/regulator	Principal role	Relevance to grain/food quality	Primary citation
Wx (GBSSI)	Major determinant of amylose biosynthesis	Influences AAC, cooked-rice texture, pasting and retrogradation	Huang et al. (2021)
SSIIa/ALK	Amylopectin chain elongation	Major determinant of gelatinization temperature and cooking properties	Waters et al. (2006)
SBEIIb	Formation of amylopectin branch architecture	Influences chain-length distribution, starch structure and digestibility	Butardo et al. (2011)
OsbZIP58	Transcriptional regulation of starch-biosynthetic genes	Influences starch accumulation and endosperm development	J.-C. Wang et al. (2013)
FLO2	Regulation of endosperm development and starch synthesis	Influences endosperm structure and grain-quality characteristics	She et al. (2010)
GW2	Regulation of grain size through control of cell proliferation	Influences grain architecture and can affect nutritional characteristics	Achary & Reddy (2021)

3.2 Climate-Related Environmental Modifications of Grain Quality

Environmental conditions during reproductive development and grain filling can substantially modify the expression of genetically determined rice-quality traits. Among climate-related stresses, high temperature, drought, and salinity are particularly important because they disrupt carbon assimilation, assimilate translocation, endosperm development, and the accumulation of starch and storage proteins. The magnitude of these effects varies among genotypes and with the timing and intensity of stress, providing the physiological basis for genotype × environment (G × E) interactions in grain quality (Shi et al., 2017; Fernando et al., 2025). High temperature during grain filling is one of the most consistently reported environmental determinants of rice quality. Heat can disrupt starch biosynthesis and endosperm development, resulting in altered amylose content, amylopectin structure, gelatinization behavior, and starch-granule organization. Incomplete or irregular packing of starch granules is also associated with increased chalkiness, which reduces grain appearance and can increase susceptibility to breakage during milling (Shi et al., 2017; Liu et al., 2025). Heat-induced changes in protein accumulation and starch–protein organization may further influence subsequent cooking and textural properties.

Drought and salinity affect grain quality through partly different physiological mechanisms. Water deficit reduces photosynthetic carbon supply and assimilates translocation and can accelerate grain maturation, thereby modifying starch accumulation, grain filling, and physicochemical characteristics. Salinity imposes both osmotic and ionic stress, disrupting nutrient transport and metabolic processes involved in grain development. Depending on genotype, developmental stage, and stress intensity, these stresses can alter grain composition, appearance, starch functionality, protein characteristics, and nutritional quality (Fernando et al., 2025). Importantly, environmental stress does not act on a uniform grain substrate. Genotypes differ in their sensitivity to heat, drought, and salinity and therefore in the extent to which grain-quality characteristics are modified under stress (Shi et al., 2017). The harvested grain should consequently be viewed as an environmentally conditioned molecular and structural phenotype, rather than a direct expression of genotype alone. This distinction is central to the proposed framework because environmental modification of starch, proteins, lipids, and grain structure can subsequently influence how the grain responds to milling, thermal treatment, cooking, and other processing operations.

3.3 Postharvest Processing Transformations of Grain Quality

Postharvest processing transforms the composition and structure of harvested rice and therefore plays a major role in determining final food quality. Milling removes the bran and outer grain layers, improving appearance and storage characteristics but reducing fiber, micronutrients, lipids, and bioactive compounds (Atungulu & Pan, 2014). Parboiling modifies the endosperm through hydrothermal treatment and starch gelatinization, which can improve milling resistance, nutrient retention, and cooked-grain firmness (Derycke et al., 2005). Cooking and subsequent cooling further reorganize the starch matrix. Cooking induces starch gelatinization and granule swelling, whereas cooling promotes retrogradation and the formation of resistant starch, thereby affecting texture and digestibility (H. Li et al., 2016; Sonia et al., 2015). Germination and fermentation modify rice through endogenous enzymatic or microbial activity and can alter bioactive compounds, nutrient availability, and digestibility (do Nascimento et al., 2024; Jiang et al., 2024). Importantly, these processing effects depend on the composition and structure of the harvested grain. Genotypic differences and environmentally induced changes in starch, protein, lipids, and grain architecture may therefore influence how rice responds to processing. Table 2 summarizes the principal postharvest processes and their major effects on rice food quality. Processing should consequently be considered an integral component of rice-quality resilience rather than an independent postharvest step.

Table 2. Major postharvest processes and their effects on rice food quality

Processing method	Principal transformation	Major food-quality consequence	Reference
Milling	Removal of bran and germ	Improved whiteness but reduced fiber, lipids, and bioactive compounds	(Atungulu & Pan, 2014)
Parboiling	Hydrothermal starch reorganization	Modified texture, grain integrity, and starch digestibility	(Derycke et al., 2005; Rocha-Villarreal et al., 2018)
Cooking	Starch gelatinization and matrix disruption	Determines softness, stickiness, and digestibility	(H. Li et al., 2016)
Cooling/reheating	Starch retrogradation and reassociation	May increase resistant starch and modify texture	(Nakayoshi et al., 2015; Sonia, 2015)
Germination	Enzymatic mobilization of stored compounds	Alters nutrients, bioactives, and starch functionality	(do Nascimento et al., 2024)
Fermentation	Microbial and enzymatic transformation	Modifies digestibility, metabolites, and nutrient accessibility	(Jiang et al., 2024; Tu et al., 2021)

4. GENOTYPE × ENVIRONMENT × PROCESSING: AN INTEGRATED FRAMEWORK

4.1 Conceptualizing the G × E × P Interaction

The preceding evidence indicates that final rice food quality cannot be attributed to genotype, growing environment, or processing independently. Genotype (G) establishes the underlying quality potential, environment (E) modifies the developing grain phenotype, and processing (P) subsequently transforms that phenotype into the final food product. Climate-resilient rice quality can therefore be conceptualized as the capacity to maintain desirable technological, nutritional, and sensory characteristics after environmental exposure and subsequent processing. The proposed G × E × P framework extends established pairwise relationships by considering whether processing responses depend jointly on genotype and the environment experienced during grain development. Conceptually, this relationship can be represented as:

$$\mathbf{Y = \mu + G + E + P + G \times E + G \times P + E \times P + G \times E \times P + \varepsilon}$$

where Y represents a measurable rice-quality outcome, such as pasting viscosity, cooked-grain hardness, resistant starch content, or nutrient retention; μ is the overall mean; G, E, and P represent the main effects of genotype, environment, and processing, respectively; and the interaction terms represent conditional responses among these factors. In this framework, a G × E × P interaction occurs when the effect of a processing treatment on a quality trait depends jointly on both genotype and the preharvest environment. The framework does not assume that all three-way effects are necessarily synergistic or multiplicative; rather, empirical evidence should determine their magnitude and direction.

Importantly, the evidence base does not prove a true three-way G × E × P interaction for all quality traits studied in this review. Importantly, the available evidence does not establish a universal three-way G × E × P interaction. Most studies demonstrate individual or pairwise relationships among genotype, environment, and processing, whereas direct factorial evidence integrating all three components remains limited. The proposed framework should therefore be regarded as an evidence-informed conceptual synthesis and an empirically testable model rather than an established universal interaction. The proposed framework is based on these pairwise relationships, but the statistical evidence for the three-way interaction should not be taken as evidence of the actual three-way relationship. The same experimental system would be required to compare more than one genotype across a set of defined environments, estimate the interaction component within a defined environment under the standardized processing treatment, and estimate the direct G × E × P component. The present framework should therefore be considered a conceptual synthesis based on evidence and a model that can be tested experimentally, but not a universally accepted three-way interaction.

The evidence supporting this continuum is therefore heterogeneous in directness. Some links are experimentally demonstrated within individual studies, while others emerge from combining findings from separate but mechanistically related studies. For example, genotype-dependent differences in starch composition and structure have been experimentally linked to processing and eating-quality traits, and environmental stresses such as high temperature have independently been shown to modify starch deposition, chalkiness, and other grain characteristics. However, studies that simultaneously track genotype, environmental exposure, processing treatment, and final food functionality remain less common. The integrated pathway presented here should therefore be interpreted at two levels: experimentally demonstrated pairwise or partial pathways, and an evidence-informed G × E × P synthesis that identifies how these pathways may connect across the farm-to-food continuum.

Figure 1 depicts this proposed continuum, connecting genetic determinants with the climate-change environment, grain molecular phenotype with processing transformations, and final food functionality. The framework highlights that climate impacts can also be felt beyond the field – environmental modification of grain composition can carry over to the postharvest phase and eventually have impacts on technological and nutritional properties for consumers (Yao et al., 2020; Zhang et al., 2022).

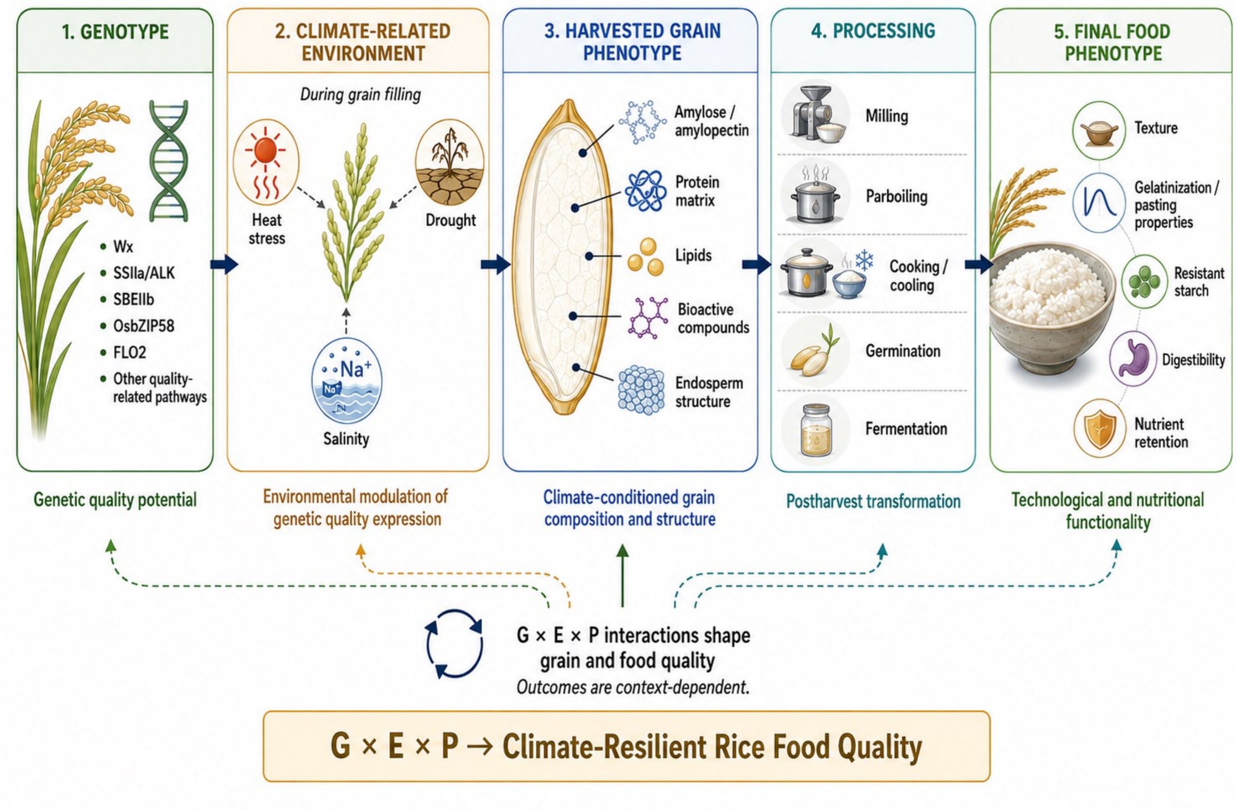

Figure 1. Author-proposed conceptual framework (illustrating the genotype × environment × processing (G × E × P) continuum in rice quality)

Genetic determinants establish the baseline potential for rice grain composition and structure, while climate-related stresses, particularly heat, drought, and salinity during grain filling, modulate the expression of these traits. The resulting climate-conditioned grain phenotype subsequently responds to postharvest processing, including milling, parboiling, cooking and cooling, germination, and fermentation, ultimately determining technological and nutritional food functionality. The framework emphasizes that final rice food quality emerges from context-dependent interactions among genotype, environment, and processing (G × E × P). The arrows represent proposed relationships and conceptual information flow rather than universally validated causal relationships; direct experimental evidence for simultaneous three-way G × E × P interactions remain limited.

As a concrete example of the G × E × P perspective, consider a rice genotype with a certain amylose content and amylopectin structure under an optimal grain-filling environment. Under elevated temperature during grain filling, the same genotype could change in starch biosynthesis, granule organization, amylose deposition, and other physicochemical properties of the harvested grain (Yao et al., 2020). Grain from both environments could then be parboiled using the same process, which might result in varying extents of gelatinization, starch reassociation, texture, and digestibility, as parboiling responses are influenced by differences in starch organization and amylose content (W. Zhang et al., 2022). The resulting food-quality outcome is thus due not only to genotype, environment, or processing, but to a combination of all three. For any trait, for example cooked-grain hardness, pasting viscosity, or resistant starch content, a significant G × E × P term in a factorial experiment would mean the processing effect is dependent on both the genotype and the environment in which the grain was produced. This example shows how the proposed framework can be transformed from a sequential conceptual pathway into an empirically testable interaction model.

A key feature of this framework is that a good quality under one production or processing condition may not necessarily be maintained under other conditions. The cultivar deemed appropriate for a particular food use may not perform similarly under heat or water stress, and processing conditions that produce a good response in one cultivar may not do the same for another. Thus, assessing quality resilience must involve not only testing whether a cultivar can produce acceptable grain quality under climatic stress, but also whether the climatically stressed grain has good functionality during processing.

This view also reveals several significant research gaps. Few experimental designs have simultaneously compared different genotypes, contrasting climatic conditions and standardized processing treatments, and assessed molecular composition alongside final food properties (Siebenmorgen et al., 2013; Xie et al., 2024). Typical approaches to studying final grain yield or harvested-grain quality and processing research often start with commercial rice samples with little information about the environment in which they were grown. This separation can be complicated because it is unclear whether variability in cooking behavior and/or digestibility is due to the genotype, the production environment, or a combination of processing conditions and genetic origin.

Thus, future G × E × P studies should use replicated factorial designs in which multiple rice genotypes are exposed to well-defined environmental conditions, and the harvested grain from each genotype × environment combination is then subjected to standardized processing treatments. Such designs would allow direct estimation of the main effects of G, E, and P, and the G × E, G × P, E × P, and G × E × P interaction components, for molecular, physicochemical, technological, and nutritional quality traits. This integrated experimentation would identify cultivars that remain relatively consistent in quality across climatic zones and processing methods, rather than cultivars that perform best only under specific growing conditions (Xie et al., 2024).

4.2 Limitations and Challenges of the G × E × P Framework

The G × E × P framework does not imply that all rice-quality traits exhibit strong three-way interactions. The relative contributions of genotype, environment, and processing are trait-specific, and some characteristics may be dominated by one or two factors (K. Li et al., 2017; Xie et al., 2024). The framework should therefore be used to test, rather than assume, interaction effects for specific quality outcomes. A further limitation is the experimental complexity of fully factorial G × E × P designs, particularly when multiple genotypes, environments, processing treatments, and replications are considered. A practical alternative is a staged approach in which important G × E responses are first identified, followed by standardized processing evaluation of selected grain samples. Thus, the framework is most useful when interaction effects are biologically meaningful and relevant to breeding, processing, or end-use decisions.

Overall, rice-quality resilience should extend beyond maintaining yield or grain appearance under stress to preserving desirable technological and nutritional characteristics from crop development to the final food product (Siebenmorgen et al., 2013; Xie et al., 2024).

5. STRATEGIES FOR CLIMATE-RESILIENT RICE FOOD SYSTEMS

5.1 Integrating Grain Quality into Climate-Resilient Breeding

Breeding for climate resilience should consider not only yield and stress tolerance but also the stability of grain-quality and processing characteristics. Molecular breeding, genomic approaches, and gene editing provide opportunities to target genes associated with starch composition, endosperm development, nutritional quality, and other quality-related traits (Achary & Reddy, 2021; Alam et al., 2024). However, candidate genotypes should ultimately be evaluated across contrasting environments and processing conditions to determine whether desirable quality characteristics remain stable from harvest to consumption.

5.2 Processing as a Quality-Adaptation Strategy

Processing provides an additional opportunity to manage variability in climate-affected grain. Milling, parboiling, cooking, cooling, germination, and fermentation can modify grain structure, nutrient retention, texture, and digestibility (Atungulu & Pan, 2014; Chinma et al., 2024). Rather than assuming that a single processing protocol is optimal for all raw materials, processing conditions could be adapted to the physicochemical characteristics of different genotype–environment combinations. Such an approach may help maintain more consistent end-use quality while recognizing that processing modifies, rather than fully reverses, stress-induced changes in the grain.

5.3 Integrating Breeding, Processing, and the Value Chain

Implementation of the G × E × P framework requires stronger coordination among breeders, crop physiologists, cereal chemists, food processors, and end users. Grain-quality assessment should therefore extend beyond conventional appearance and yield measurements to include processing performance, physicochemical functionality, nutritional characteristics, and consumer-relevant traits. Linking these measurements across breeding and processing pipelines could support the development of cultivars and processing strategies better suited to increasingly variable production environments.

6. CONCLUSION AND FUTURE DIRECTIONS

Rice quality under climate change should not be considered a fixed characteristic measured only at harvest. Genetic potential (G) is modified by the growing environment (E), producing a harvested grain phenotype that is subsequently transformed through processing (P). Integrating these stages provides a more complete basis for understanding climate resilience from grain development to final food quality. Available evidence strongly supports important relationships among genotype, environment, grain composition, and processing; however, direct experimental evidence for a universal three-way G × E × P interaction remains limited. The framework proposed in this review should therefore be regarded as an evidence-informed and empirically testable model, rather than an established universal interaction.

Future research should prioritize factorial G × E × P experiments, particularly for major end-use traits such as texture, starch digestibility, resistant starch, nutrient retention, and processing performance. Multi-stress experiments, standardized micro-processing assays, and sensory evaluation should also be incorporated where appropriate. Ultimately, climate-resilient rice development should aim not only to maintain production under stress but also to deliver stable, nutritious, processable, and acceptable food products.

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