

Gel Consistency in Rice: Genetic Mechanisms, Starch Properties, and Culinary Quality – A Comprehensive Review

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Keywords: Nursing values, future time perspective, problem-solving proficiency, nurse interns.

Received on 25 July 2025

Accepted on 27 Aug 2025

Published on 06 Sep 2025

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Gel consistency (GC) is the vital deciding factor of cooked rice texture together with consumer preference that is strongly predisposed by genetic, environmental, and procedural effects. The most recent developments that are synthesized in the current review show that GC is highly affected by the Waxy (Wx) gene and quantitative trait loci (QTLs) that mediate the production of amylose, the mechanization of which indicates that softer texture is linked with low levels of amylose which is subsequently associated with higher GC. Environmental modulation is high: overuse of nitrogen fertilizers increases amylose levels, or toughens texture and deficient water leads to the decrease of GC; the optimal alternative wetting and drying (AWD) irrigation, however, increases the levels of GC. Methodological instruments, such as the Alkali Spreading Value (ASV) and the Rapid Visco Analyzer (RVA), can be used to give objective and quantitative measures of the

physicochemical properties, and these are supplemented by sensory and rheological investigations, which relate the metrics to perception by the consumer. There is strong cultivar divergence: indica types tend to have harder GC, which is suited to cooking in South Asia, japonica types have softer GC, and is appropriate in East Asia, an indication of the genotype-by-environment interaction. High-GC rice has a high market value of culinary uses, but hard-GC is not accepted in the market. Attention should be focused on combined genotypic-environment stability, resource sustainability, nutritional quality, in order to fulfill emerging consumer and climatic needs.

Key Words: gel consistency (GC), amylose content, rice breeding, QTL, rice quality traits, sensory quality

Introduction:

Gel consistency (GC) is a critical quality aspect in the rice that plays an important role in determining not only the cooking but also functional aspects of the cooked rice. The particle size of cooked rice is a direct effect of the GC, hence, determining the consumer preferences, who then decide whether to use the rice in specific applications or not. In food-science terms, GC is a measurable parameter of how really firm or soft the rice will eventually be cooked then cooled; knowledge of this is essential to assessing the rice suitability to specific foods and final applications. As a result, cultures around the globe have traditional tastes whereby they prefer rice to have particular textures. The detailed knowledge of the factors that can regulate GC is therefore not only necessary, but also the possible resort of rice breeders and food scientists to come up with varieties that suit the growing needs of the people.

Mechanistically, GC is mediated to a great extent by the chemical composition of rice starch, specifically amylose: amylopectin ratio. One of them, amylose is a linear polymeric compound, which significantly affects the structural characteristics of the rice gel, the rate and extent of retrogradation (Chen *et al.*, 2024). The starch granules in rice absorb water and swell during cooking; they become gelatinized by heat. This gelation process as well as the firmness of cooked rice is governed by the balance between the amylose and amylopectin molecules and the type of configuration as to their structure. Higher percentage of amylose usually leads to stiffer, drier rice, conversely, lower percentage of amylose leads to softer,

sticky texture which is a desirable quality when it comes to Japanese cuisine including sushi, and other Asian rice cakes (Wang *et al.*, 2024).

Recent research activities have revealed a significant difference in viscosity of gels in between different rice cultivars, which is closely attributed to different genomic make up. Monitored gel rigidity data proves the notion to be true that the individual cultivars have their specific values, which subsequently shape the quality and tell how each cultivar can be applied to different culinary tasks (Hu *et al.*, 2022). The inter-cultivar variations phenomenon poses the importance of the availability of the comprehensive databases where the gel consistency data are enriched by additional physicochemical parameters, mainly gelatinization temperature and pasting viscosity. These characteristics depict a complex multi-factorial, reciprocal interaction with gel consistency hence making the characterization and use of cultivar-specific starch qualities difficult to utilize (Gao *et al.*, 2023). The development of molecular genetics over recent years has led to elucidation of the alleles and genes that produce such characteristics, which makes a way to breeding plans more specific, creating breeding plans that focus more on gel-consistency factors in creating new rice varieties (Liu *et al.*, 2022).

When it comes to rice breeding, particular emphasis has been placed on quality traits that could be associated with the cooking and eating qualities of rice since said factors are increasingly determining market conditions, and consumer spending habits. Genetics studies have described quantitative trait loci (QTL) mapping of the gel consistency confirming that the trait is heritable and variable and therefore can be readily selected (Chakraborty *et al.*, 2024). Or strong associations between the markers and gel consistency have been determined by empirical results hence allowing use of marker assisted selection to be used in a general way aimed at enhancement of desired rice quality traits. The genetic factors behind such traits also have the potential to be used to overcome future challenges regarding rice production inheritance application, such as the challenges of climate change, changing consumer demands, and the need to have sustainable agricultural practices (Iftikhar *et al.*, 2020). The current review thus aims at a thorough analysis of the current approaches to deciphering the gel consistency, audit of the genetic basis upon which this outstanding agronomic trait depends, and critically assessing the significance of gel consistency with regard to modern rice breeding. By doing so, it offers a state of art synoptic view that helps us to understand the current state of study on the gel consistency, and how the given attribute becomes the focus of study and attention to improve the quality of rice which is continuously being affected by various heterogeneous consumer environments.

Methodological Approaches to Gel Consistency Measurement

Determination of gel consistency (GC) can be considered very important as it plays a significant role in the texture and culinary uses of cooked rice. In the field of cereal science, the alkali spreading value (ASV) technique has become the most commonly used technique to determine the dispersion ability of cooked rice in alkaline medium. In the process, a sample of rice is cooked, cooled after which it is exposed to a weak alkaline solution. The results of the ASV suggest that a lower reading might comprise a firmer texture and denote the higher amylose content, and vice versa, a higher ASV reading represents a softer texture, generally typical of the rice varieties with reduced amylose content and a more significant GC value (Nakamura *et al.*, 2021; Bao *et al.*, 2023). The ASV technique is easy, convenient, cheap and useful to determine characteristic textural properties of the rice.

In addition to ASV, other studies today have focused on the benefits of Rapid Visco Analyzers (RVA) in the estimation of the gel consistency. Besides enabling the

measurement of pasting viscosity, RVA provides information, as characterized by the evaluation of viscosity parameters (breakdown (BD) and setback (SB) values. As already shown in the literature, rice cultivars with high levels of gel consistency have low BD and SB values cited through RVA referred to as stable gel structure through cooking (Lu *et al.*, 2023; Al-Askar *et al.*, 2024). The study of numerous parameters of viscosity in a single measurement is contributing to the overall interpretation of the cooking quality among different rice genotypes, thus facilitating efforts to improve both cooking and eating qualities through breeding efforts.

The environmental factors are influential in manifesting the consistency of the gel in rice. Other effects of environment on ASV and RVA happen through the interaction of rice genome with other factors, including soil type, irrigation regimes, and fertilizer application that affect the moisture uptake by the rice during the cooking process. According to empirical evidence, the period of post-anthesis irrigation is well linked with gel quality, where the utilization of systematic and timely irrigation greatly increases the texture of mature grains (Rayee *et al.*, 2021; Hu *et al.*, 2022). Further investigations show that the level of fertilizer nitrogen also plays a key role in determining the properties of the gel: the well-adjusted effect of N leads to increased starch properties, contributing to a desirable profile of gel consistency (Wang *et al.*, 2024).

According to the literature, significant shifts have been observed in the simultaneous utilization of the pre-existing measurement protocols. With the combination of ASV, RVA and sensory analyses, researchers will be able to combine the objective measures with the consumer-based perceptions of quality, taste, and textures. Even more detailed breaking down of gel structure is provided by routine rheological analyses, which explains the economic feasibility of a particular cultivar (Zhang *et al.*, 2022). There are different methodological approaches shown in table 1 for measuring gel consistency of rice.

Table 1: Methodological Approaches for Measuring Gel Consistency in Rice

| Sr | Methods | Parameters Measure | Advantages | Limitations | References |
|----|------------------------------|---|--|---|---|
| 1 | Alkali Spreading Value (ASV) | Alkali digestion score (1-7 scale) Gel length (mm) | Simple, low-cost, rapid High correlation with amylose content & texture | Subjective scoring Sensitive to sample preparation | (Nakamura <i>et al.</i> , 2021) (Bao <i>et al.</i> , 2023) |
| 2 | Rapid Visco Analyzer (RVA) | Peak viscosity (cP) Breakdown (cP) Setback (cP) | Quantifies multiple traits High reproducibility | Expensive equipment Requires standardized protocols | (Lu <i>et al.</i> , 2023) (Al-Askar <i>et al.</i> , 2024) |
| 3 | Sensory Evaluation | Softness/stickiness (5-point scale) Mouthfeel | Direct consumer relevance Holistic quality assessment | Subjectivity Time/labor-intensive | (Zhang <i>et al.</i> , 2022) |
| 4 | Rheological Analysis | Storage/loss modulus (G'/G'') Gel strength (Pa) | Precise gel structure characterization Objective texture quantification | Specialized expertise required Limited field application | (Rayee <i>et al.</i> , 2021) |

| | | | | | |
|---|---------------------|-------------------------|--|-----------------------------|---|
| 5 | Integrated Approach | Multi-parameter indices | Comprehensive quality profiling Predicts real-world performance | Data integration complexity | (Li <i>et al.</i> , 2018) (Gao <i>et al.</i> , 2023) |
|---|---------------------|-------------------------|--|-----------------------------|---|

The use of advanced statistical techniques to analyze the results obtained after measuring using both ASV and RVA has become more common, and it allows investors to correlate sensory factors to physicochemical parameters with much more accuracy. With the application of these analytical models, researchers are in extra knowledge regarding the epidemiologic aspects of the genetic determinants of gel consistency especially in studies that are aimed at advancing the rice breeding procedures. Although the traditional breeding programs previously focused on yield and disease resistance, the recent improvements make it clear that the inclusion of quality traits like gel consistency in the breeding programs focused on higher consumer satisfaction is necessary (Rayee *et al.*, 202; Li *et al.*, 2018).

There has been a convergence between technological innovation and research methodology that has changed rice gel assessment such that it produces a comprehensive view of the interaction between the genetic and agronomic factors. Such an integrated study does not only complement our understanding of rice quality traits but the analysis provides a sound platform to create rice cultivars that would give satisfaction to marketplace requirements and consumer taste.

Influence of Environmental Factors on Gel Consistency

The impact of environmental factors is drastic on GC in rice, and these shapes the cooking characteristics of rice and further consumer satisfaction on this pillar cereal. Fertilization practices are some of the most important modulators of GC in the context of environmental determinants. Empirically, over-fertilization of nitrogen has been observed to negatively affect GC on the by-product that has been depicted by distortion in starch composition, finally resulting in cooked rice with a tougher texture (Nakamura *et al.*, 2021; Bao *et al.*, 2023). Increased plant nitrogen concentration supplied by enriched nitrogen levels in soil is more supportive, but it can also increase some growth parameters and, at the same time, influence starch composition raising the Nitrogen management is the essential aspect within the rice farming unit; irrigation on the other hand exhibits equally profound control over the gel consistency. Rice is economically, energetically, and ecologically a water-intensive crop and adoption of efficient irrigation practices has been shown to empirically increase water-use efficiency and subsequently, better results in rice quality production (Wang *et al.*, 2024). Modern science is thus focusing on the developments in the irrigation management that seeks to maximize both the productivity of water and gel consistency at the same run. Rayee *et al.*, (2021) examined the various irrigation regimes and have shown how various rice irrigation regimes alter the growth requirements, thus affecting the levels of amylose in the various rice cultivars and thus affecting their gel consistency properties. Irrigation is the other key factor, which helps in granting the crop the best growth and development which has a direct influence on the genetic expression concerning the starch synthesis.

The empirical evidence of such interaction between the water stress and the gel strength has revealed that in the case of poor irrigation management, low-quality rice may be produced. Drought stress at the critical growth stages, say, has been associated with reduced values of gel consistency as limited water supply inhibits the attainment of desirable features in terms of starch constitution (Rayee *et al.*, 2021). Further investigations reveal that the preservation of proper soil moisture levels, especially at the grain-fill period of growth, ensures efficient maximization of the gel consistency

and overall quality of growing grain (Li *et al.*, 2018; Wang *et al.*, 2019). Reliable reviews establish the fact that climate change is aggravating the aspects of water scarcity, a process that jeopardizes the sustainability and dependability of irrigation channels that are necessary in producing rice (Ponce *et al.*, 2018). The levels of amylose constituents that, in turn make the gel stiffer (Lu *et al.*, 2023). Controlling the levels of nitrogen has been observed to improve grain quality due to the support of the ideal amylose to amylopectin ratio through use of calibrated applications of nitrogen to match the specific needs of specific varieties of rice strains (Al-Askar *et al.*, 2024; Hu *et al.*, 2022).

Al-Askar *et al.*, (2024) noted that the triumph of nitrogen application is expected at an optimal level leading to an enhancement of GC in comparison to excessive fertilizer practice, thus promoting the notion of improved nitrogen management tactics (Nakamura *et al.*, 2021). This result supports that experienced by Hu *et al.*, (2022), where the team has observed that there is a negative relationship between rates of nitrogen fertilizer and GC, and thus, moderate application levels signify locking down the best levels of cooking quality. Wang *et al.*, (2024) stress that the balanced nitrogen fertilization does not only pave the way to the higher GC but also does it so by facilitating the maximization of other quality traits in terms of which commercial rice making is crucial, thus creating the dilemma of boosting yields and ensuring top-notch GC (Lu *et al.*, 2023; Al-Askar *et al.*, 2024).

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Table 2: Environmental Factors Affecting Gel Consistency in Rice

| Sr. | Factors | Impact on GC | References |
|-----|----------------------|---|---|
| 1 | Nitrogen Fertilizers | Excessive nitrogen causes lower GC (hard texture) | (Al-Askar <i>et al.</i> , 2024) (Hu <i>et al.</i> , 2022) (Wang <i>et al.</i> , 2024) |

| | | | |
|---|----------------------|---|--|
| 2 | Irrigation Practices | Water stress lowers the GC (hard texture) | (Zhang et al., 2022) (Rayee et al., 2021) (Kim et al., 2021) |
| 3 | Climate Interactions | High temperature and water scarcity lowers the GC (hard texture) | (Ponce et al., 2018) (Mukamuhirwa et al., 2019) |
| 4 | Soil Composition | Lower water retention causes high amylose which lower GC (hard texture) Clay soils high micronutrients high starch quality | (Bhati et al., 2022) (Gao et al., 2023) |

Such water saving irrigation regimes as alternate wetting and drying (AWD) efficiency has proved successful at maintaining or improving the gel consistency important to rice grain quality (Kim et al., 2021). A comparative study on in-situ advanced-water-management practice (AWD) and with an extended period of flooding revealed that AWD managed to increase nitrogen use efficiency very much, and also successfully maintained or, even in some circumstances, even augmented grain gel consistency (Zhang et al., 2022). These results highlight AWD as a potentially valuable tool to both conserve water and at the same time to maximize nitrogen use efficiency, which will assist in optimization of grain quality traits that form part of sustainability goals in rice production. As a supplement to clarifying the importance of AWD, Yang et al., (2018) additionally noted the secondary advantages of the given solution, i.e., the reduction in methane emissions, as well as the adoption of effective methods of water management, in turn, demonstrating how modern rice-production processes can contribute to the cultivation of environment-friendly agriculture.

Genetic Controls and QTL Mapping

The genetic architecture of rice is known to be complex, i.e., many quantitative trait loci (QTL) interact with each other, which is especially the case in traits related to cooking quality, in particular gel consistency (GC). A great deal of evidence has been used to map many QTL controlling GC, especially those modifying amylose concentrations and starch characteristics. The key gene in amylose biosynthesis, the Wx (Waxy) gene, has been reported many times to mediate gel consistency. All of the studies reported a consistently negative correlation between the levels of amylose and GC, which means that the lower the concentration of amylose is, the softer the gel and, therefore, the higher the GC values (Hu et al., 2022).

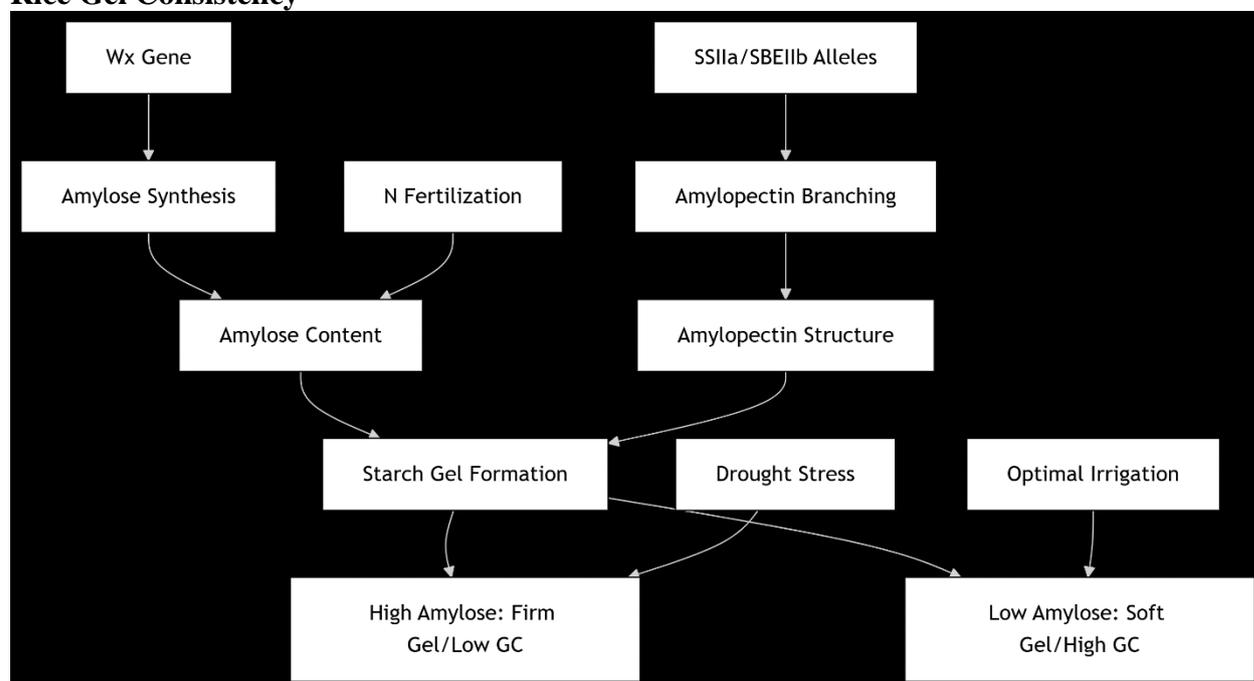
Other than the Wx gene, other loci have also been demonstrated to have an impact on the variations in GC. As an example, Huang et al., (2024) associated allelic variations of the genes involved in starch synthesis with different GC and alkali spreading values. Their findings showed that the presence of specific alleles in the hybrid rice line led to better texture profile that are suggestive of improved cooking quality (Huang et al., 2024). The results therefore highlight the prospects of using genetic diversity in breeding to start with the intent of improving the gel consistency at large levels of cultivars.

With the introduction of the marker-assisted selection (MAS) in the breath of rice breeding, it was observed that this process is a remunerative and time-saving way of introducing desirable gel consistency attributes in elite rice lines. Here Xiao et al., (2025) proved its usefulness by introducing MAS in order to utilize genetic variation at the Wx loci which brought about rice lines with desirable cooking phenotypes and better reception by consumers (Xiao et al., 2025). MAS lessens the reliance on

traditional breeding which is often time consuming and laborious by utilizing individuals which have the so-called genetic marker that are linked to excellent gel consistency and other quality attributes.

It has also aided breeding by allowing a level of precision breeding using mapped genomic regions affecting the gel consistency trait and the efficiency of the breeding program targeting this quality trait in rice. The integration of the genomic technologies with quantitative-trait locus (QTL) mapping will allow a more precise resolution of the genetic architecture of gel consistency. According to Yang et al., (2018), there was a strong correlation between the gel consistency and multiple other quantitative traits, demonstrating that the selection of one trait can have positive impacts on other desirable traits (Yang et al., 2018). Such a pattern of interactions indicates that a multi-trait breeding strategy may produce higher overall quality rice cultivars.

Figure 1: Conceptual Diagram - Genetic & Biochemical Pathways Influencing Rice Gel Consistency



The discovery of new genomic techniques in recent years e.g. genome-wide association studies (GWAS) and next-generation sequencing as well as the newly developed gel consistency-related traits in studies have increased the possibility to find quantitative trait locus (QTL) associations by a significant margin. The authors assigned in their work reported by Zhang et al., (2022) used the high-throughput sequencing to outline particular genes essential to both gel consistency and flavor quality of rice, thus, offering an adequate empirical basis to serve as a precision breeding intervention towards refining phenotypic features of both the rice varieties (Zhang et al., 2022). This comprehensive information is very essential, as preference of consumers is drifting towards varieties of rice that not only have a good cooking quality but also have improved sensory quality.

There is a very strong genetic variation of genetic mediated gel consistency modulated by environmental conditions on quantitative and qualitative behavior. Styles of climatic conditions, soil properties and agronomic procedures have the ability to influence the phenotypic expression of quantitative trait loci (QTLs) required in gel formation. As it had been shown in a recent study, the genotype-environment interaction effects on gel consistency (GC) and the need of including

these environmental factors in the breeding programs to achieve consistent quality was reflected (Jena et al., 2018). As a result, all initiatives on augmenting the consistency of the gel on specific crops should be employed with a keen cultivation approach that ensures that growing conditions are enhanced.

Variation Across Rice Cultivars

The existence of variation in cultivars is an element of agronomic and genetic concern raised to the frontiers of inquiry particularly in the manner that different races portray varied characteristics under a set of specific environments. This source of variation is often referred to as genotype-by-environment interaction ($G \times E$), which plays a significant role in determining the quality characters and agronomic behavior of *Oryza sativa*. Due to the influence of temperature regimes, soil type, and cultivation methods, genotypes react differently and finally define the productivity and the suitability of the market specificity (Hairmansis et al., 2022; Zhao et al., 2024).

This indicates that in general, hard gel consistency as an attribute of major economic value is stronger in indica compared to japonica cultivars. Such a phenomenon brings to the fore substantial genetic difference among the two groups and, by extension, influences culinary usage and acceptance by the consumer (Sampaio et al., 2021). The preference of Indica rice types thus is within areas in which firmer textured rice is preferred and this is in line with local food practices and the tastes of the market. In comparison, the japonica rice variety that has a more amenable texture manages to capture the markets with a preference toward mild tastes in food preparation (Chen et al., 2023). These genetic variations have practical implications to modern breeding programmes, as it should conform cultivar properties with consumer taste relating to the local regions and must be both agronomically robust and covered by the market demand (Kreungnern et al., 2021).

Rice quality manipulation does not only depend on the genetic material of specific cultivars since it will also involve accurate consideration of the level of interaction between existing environmental situations and specific varieties. Recent integrative studies exhibit an adaptive mechanism in terms of yield stability that some cultivars are capable of yield in wide-ranging soil characteristics and climatic ranges making it a new dimension to modern-day breeding discussion (Ali et al., 2020). It is necessary to adapt to changing agronomic conditions and unstable agricultural conditions, as was mentioned before to ensure food security, it is important to identify progenies that combine high yields and steady performance in changing agronomic regimes (Selle et al., 2020).

The evolution of rice breeding depends progressively on integrating the collection of environmental data with complex data pertaining to the genome. It is a complex approach that has a better way of capturing $G \times E$ interaction and is used to predict more accurately how a given cultivar will perform within specific ecological conditions (Crossa et al., 2025). Additive main effects and multiplicative interaction (AMMI) model is known to be one of the statistical techniques commonly used in disentangling and simplifying breeding operations when complex genetic-environment interactions are involved (Daemo et al., 2023). Through such methodologies, breeders can gain visualization of how different cultivars respond to diverse environmental conditions and hence making it easy to select high-performing genotypes that perform favorably in a wide range of agro-climatic conditions (Abebrese et al., 2019).

The heterogeneous environments and the simultaneous combination of the intrinsic genetic ability of the cultivars and the variation in transmission and expression of a characteristic trait under different environments characterization of rice performance (Xuan et al., 2020). Other recent studies highlight that this flexibility is crucial in the

development of crops that can resist the frequency of extreme weather events that are becoming common due to climate change (Mukamuhirwa et al., 2019). In turn, modern practices in the field of studying genetics of rice are aimed at creating lines that will not only meet contemporary demands of the agrarian sector, but also demonstrate the stability to thrive in conditions of climatic instability in the future (Mau et al., 2019).

Genetic categories are explaining trait determinants that impact on rice quality using specific analysis. Empirical evidence indicates that genotype has a high determinant impact on values of amylose, gelatinizing temperature, and cooking quality- which are among the factors heavily influencing consumer preferences and thus need to be prioritized in breeding programs on a global level (Amalia et al., 2019). The presence of genomic regions that are correlated with these traits gives the groundwork with which precision molecular breeding can be done to hasten the production of top-quality rice varieties (Chen et al., 2023).

Recent Advances in Gel Consistency Research

Empirical studies of gel consistency in rice in the recent past have expanded modern thinking on this property of rice beyond the traditional evaluation based on amylose amylopectin ratios. The development of genomic technologies in the recent past has made it a possibility to analyze the complex gene networks that determine the textural properties. Such networks are characterized by multifactorial interaction that balances a range of chemical and morphological factors, which form the dynamics of texture all together. As an example, the article by Cheng et al., (2020) explains the interactions between starch branching enzymes and the functional implications on the gel structure, which is the feature that conclusively defines the texture and palatability of cooked rice (Hairmansis et al., 2022). The results indicate that the branching is of utmost importance to the gel formulation since the magnitude of branching is directly related to the stability of rice gel during preparation and storage.

Additional starch behavior studies show the presence of retrogradation phenomena that take place following cooking and affect consumers significantly towards acceptability. In cooked starch, retrogradation is defined as the re-combination of amylose and amylopectin chains which take place during the post-cooking cooling process and which are manifested by the discernable changes in texture with effects impacting on the mouthfeel and general quality (Zhao et al., 2024; Sampaio et al., 2021). The empirical data have shown that the behavior of starch during this retrograding period has been a key driving factor behind consumer preference of rice texture (Chen et al., 2023). Therefore, retrogradation properties are not only necessary in terms of knowing the consistency of a gel, but also in terms of knowing the nutritional effects of digestion of starch in human body.

Studies on the relationship between apparent amylose of rice that is commercially milled, and gel consistency have been undertaken consequently clarifying the connection between the gel behavior and their perception by the consumer. Tuao et al., (2021) studied the impact of ratios of amylose and amylopectin (the latter harmless) in cooked-rice properties and consumer acceptance through the photometry of digital images of cooked-rice and revealed that these biochemical constituents play an overriding role as it determines the overall sensory impression (Kreungngern et al., 2021). Findings reveal that higher levels of amylose yields a more desirable texture, which in turn has a direct impact on the consumers perception of the quality of the cooked rice dishes.

Quality Implications of Gel Consistency

Gel consistency is a basic imperative character that significantly affects receptor approval and trade capacity of rice kinds. Experimental discovery shows that in gastronomically-related terms, rice samples with high gel consistency, in which the texture is slightly elastic, are more desirable in relation to the preparation of sushi and sticky rice (Hairmansis et al., 2022; Zhao et al., 2024). These likes increase the marketability of such varieties and makes them highly appealing to customers in given markets. Prasad et al., (2021) notes that textural properties of rice have direct influence in purchase preference, especially among the population that consumes softer rice, hence confirming the hypothesis that gel firmness is a milestone of determining the variety success in the market. Here table 3 is showing global map of rice texture preference and cultivar distribution.

On the other hand, rice with hard gels content is usually linked with undesirable consumer characteristics especially in areas where readers have softer and more pleasing gel consistency (Sampaio et al., 2021). This duality highlights the importance of gel firmness in decision-making by the consumer and tends to push hard-gel rice to the less thriving market segments. Furthermore, Tadesse and Abegaz et al., (2019) report that varieties having soft textures are also in close proximity with consumers expectations that only substantiates the importance of gel consistency as a main variable in developing a product whose consumption will meet market demand (Chen et al., 2023).

The relationship between the gel consistency and market preference is not lost since recent consumer studies bear out a direct relationship between these characteristics. Comprehensive knowledge of preferences in the gel consistency would allow the breeders to carry out new rice product improvement methods leading to developing rice varieties matching the market expectations (Kreungngern et al., 2021). This type of correlation is thus crucial in determining whether new varieties of the rice meet the demands of the consumer without compromising the much-needed agronomic qualities in its production.

Also, a variety of studies has been conducted regarding the implication of gel consistency in the quality of cooking, in specific, the physicochemical characteristics of rice that impact cooking properties. Another example of the study is Hu et al., (2022) who investigated the impact of different cooking parameters on the texture of cooked rice, where one particular outcome was the importance of gel consistency that influenced sensory and texture properties of rice-based dishes (Ali et al., 2020). The quality of cooking gauging of parameters such as gel consistency are factors that should not be ignored as they influence consumer acceptability and general satisfaction.

Role of Breeding Techniques

Present-day rice-breeding has integrated modern software related to genomic selection with the older and traditional pedigree-based techniques and has consequently significantly increased the levels at which brevity and correctness are gained in generation of new varieties of rice and in particular the gel consistency. Genome-wide association studies (GWAS) are now available as a strong method to identify quantitative trait locus that support gel consistency and other associated phenotypes. The results would allow breeders to implement the deeply differentiated selection protocols that would meet different consumer requirements regarding the quality of rice (Yang et al., 2020). Empirical evidence further emphasizes that genomic selection is capable of reducing the length of breeding cycles by a sizeable margin that allows the delivery of advanced phenotypes into the commercial markets much faster (Crossa et al., 2025).

One of the representative studies conducted by Yang et al., (2020) exemplifies that the simultaneous use of GWAS and genomic selection not only increases the accuracy of trait dissection related to gel firmness but also makes it easier to breed the cultivars that will better match the preferences of consumers who seek softer gel rice as a property inherent to the cultivar as a quality feature that can be used to present their products in the form of sushi and desserts. The ability to choose genotypes with these characteristics allows the breeders to produce rices that are high yielding and at the same time sensitive to the market condition that dictate high quality.

Table 3: Global Map of Rice Texture Preferences & Cultivar Distribution

| Region | Texture Preferred | Dominant Cultivar | GC traits | Culinary Use |
|----------------|-------------------|-------------------|-------------|---------------------|
| East Asia | Soft/Sticky | Japonica | High | Sushi, Dessert |
| South Asia | Firm/Separate | Indica | Low | Biryani, Pilaf |
| Southeast Asia | Variable | Indica/Japonica | Medium-high | Sticky rice, Salads |

Concurrent developments in molecular genetics showed that marker-assisted selection (MAS) and genomic selection can be mutually reinforcing in that MAS can be used to track particular genetic markers silhouetted to gel consistency. This collaborative effort helps in fast-tracking the process of developing better rice varieties via multi-generational selection that was meant to optimize the overall grain quality (Selle et al., 2020).

The subsequent improvement in rice genetics requires the strategic discovery of new gene loci as part of gel consistency. It has been emphasized by the new work of Yang et al., (2020) that the role of GWAS in revealing the genetic underpinnings of eating and cooking quality traits, with amylose content and gelatinization temperature playing a vital role in defining the consumer preferences, is paramount in japonica rice. The general appreciation of the internal genetic systemation can empower breeders to use genomic techniques in designing cultivars that do not only act in agronomic terms but they are also highly marketable due to the cooking quality values they hold.

In addition to GWAS studies, advances in genomic selection have encouraged the need to look into other factors that contribute towards gel consistency as well. The genetic foundation of the resistant starch content has empirical results showing the interactive nature with relationship to amylose and amylopectin ratios, which opens the doors of using breeding to manipulate the trait. By systematically studying these interactions, researchers are in a position of enhancing the rice germplasm by strategic selection of variety thereby making this main food item nutritionally adequate and consumers oriented. At the same time, developing technologies like CRISPR/Cas9 gene editing enable new ways of directly editing the traits linking to gel consistency. The ability to add or subtract certain genes in favor of material producing softer textures is something that has the potential to transform breeding of high-quality cultivars that would save on time and resources normally spent on sophisticated form of breeding. Such technological change is particularly relevant given the issues of global climate, which require the creation of climate-resistant crop varieties at accelerated pace, but still allowing products to be sold in markets that are demanding specific textures.

Conclusion

Gel consistency (GC) has been used as another key criterion of rice quality that has significant impact on food texture in the kitchen, consumer preference, and

marketability. The current review systematically synthesizes the new findings that explain the multifactorial nature of GC: the primary regulation occurs at the genetic level the Waxy (Wx) locus and the complex set of its regulatory quantitative trait loci (QTL) influence amylose biosynthesis and starch structure across cultivars, lower amylose content exerts a correlation to a soft gel-formation, higher values of GC. Recent developments in genomics, i.e., genome-wide association studies (GWAS), marker-assisted selection (MAS), and genome editing via CRISPR/Cas9, have made dramatic progress in the rate at which potential allelic variants underlying biological traits of crops of potential interest to crop improvement have been identified, including the highly significant example of SSIIa and SBEIIb that are related to starch. This has led to the fact that modern precision breeding programs can now operationalize the results recorded under such methodologies to engineering new varieties that provide custom compositional profiles. GC response to environmental conditions is some of the most plastic available; nitrogen fertilizer, over application of which is disadvantageous to texture due to increased amylose production, water management (especially drought stress, which reduces GC), and Alternate Wetting and Drying (AWD) repeated wetting/drying, which improves and eliminates each factor were shown to affect GC variability. Enhanced retrogradation is observed even more extensively under heat stress condition. Advances in technology have also facilitated a combined evaluation of GC: Alkali Spreading Value (ASV) and Rapid Visco Analyzer (RVA) measure parameters of physicochemical analysis, and sensory analysis and rheological testing fill the gap between the indicators and perceptions of genuinely perceptual variables such as mouthfeel and stickiness. Germplasm diversity continues to remain an important locator, with the traits of indica varieties tending to be harder in their GC profile, hence, fitting in better to cooking traditions in South Asia, and japonica cultivars being softer, and more in tune with taste of East Asian culture, and the difference here reflects strongly the importance of genotype-by-environment (G x E) interactions within any given region.

The repercussions of grain-content (GC) variation are far-reaching: cultivars with high-GC attract higher prices in sushi, desserts, and ready-to-eat products whilst those with a harder grain texture are frequently rejected by customers in texture-perceptive zones. Eventually, it is an economic reality which requires that breeding programmers combine high GC with yield stability and climate adaptation, and this becomes increasingly urgent because climate change is intensifying abiotic stress. The future researches should focus on the deciphering of grain-content-environment interactions, optimal usage of sustainable utilization of resources, and nutritional attribute alignment (such as accumulation of resistant starch content) with culinary manifestation (textural perfection) hence, the next generation rice variety must be able to meet consumer demands and environment demands as well.

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