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REVIEW ARTICLE

Agronomic and environmental perspectives on rice grain quality

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Abstract

Asia dominates global rice production, contributing nearly 90 % of the total output, with China and India producing over 50 % of the world's rice. Rice quality is primarily determined by head rice yield, which is influenced by genetic traits, environmental conditions, agronomic practices and postharvest handling. The global rice market values high milling recovery rates, with head rice recovery (HRR) often exceeding 50 % in premium varieties. However, high nighttime temperatures, fluctuating precipitation patterns and suboptimal storage conditions significantly degrade grain quality, leading to increased chalkiness and reduced HRR. Climate change is projected to reduce rice yields by 10-15 % per 1°C rise in temperature**,** further threatening food security in monsoon-dependent regions. Utilizing crop models that integrate weather data and management practices can aid in optimizing sowing schedules and enhancing resilience in rice cultivation. This review synthesizes current research on the determinants of rice quality, examining the effects of genetic variability, drying and milling techniques and environmental stressors**.** Understanding these factors is crucial for improving rice production systems and ensuring long-term food security amidst climatic challenges.

Keywords: milling quality; post monsoon; rice quality; sowing dates; temperature

Introduction

One of the most critical food crops globally is Rice (*Oryza sativa* L.), which plays a pivotal role in sustaining livelihoods, particularly in rural India, where it provides approximately 70 % of direct employment (1). Moreover, it serves as the staple diet for billions of individuals worldwide. Given its significance, rice cultivation holds immense importance for food security across Asia, accounting for over 90 % of both production and consumption of rice in the region. Rice contributes significantly to dietary energy and protein, providing between 32 % and 59 % of dietary energy and 25 % to 44 % of dietary protein. Projections indicate a substantial increase in rice demand-expected to surge by 70 % over the next three decades to maintain current per capita availability (69 kg yr^{-1})-while also maintaining land productivity levels (2). With rice production occupying the largest portion of global land use for food production, spanning 164.1 M ha and yielding approximately 761.5 MMT of paddy annually (3), it underscores its pivotal role in global agriculture.

India, as the world's second-largest producer of rice following China, plays a significant role in global rice production dynamics. In India, rice cultivation encompasses an expansive 47.82 million hectares, resulting in an annual production of 137.82 MMT and achieving a productivity rate of 2882 kg per hectare (4) .

Rice is a staple food in many countries, predominantly consumed as whole grain and its quality is paramount compared to other cereals. Milling, physical appearance, cooking properties, sensory attributes, palatability and nutritional value influence its market price. Quality indicators like head rice yield, representing the percentage of intact grains after milling, play a crucial role. The market value of broken rice, a byproduct of milling, is substantially lower, typically ranging from 50 % - 60 % compared to head rice. Exposure to high temperatures during the ripening phase, particularly in rabi rice cultivation, can lead to adverse effects such as decreased grain weight, impaired grain filling and an increased proportion of chalky rice. The compromised physical quality of rice grains adversely impacts market prices, diminishing stakeholders' income along the value chain (5).

Three key factors underscore the importance of proper rice sowing timing. Foremost among these is ensuring that the vegetative phase aligns with favourable temperatures and abundant sunlight. Secondly, selecting the optimal planting time for each variety ensures that the stage sensitive to cold temperatures aligns with historically warmer minimum night temperatures. Lastly, timely planting ensures grain filling occurs during milder autumn temperatures, promoting better grain quality (6).

Grain yield and quality in rice are affected by various factors, including varietal characteristics, crop production practices and prevailing climatic situations. Appropriate sowing date represent simple and effective agronomic approach to enhance rice quality. Furthermore, seasonal factors have been associated with increased grain breakage during milling (7).

Major constraints in producing quality rice

Genetic and environmental factors significantly influence rice kernel appearance, dimensions, milling performance and cooking characteristics. Abiotic stresses, such as drought, salinity, submergence and high nighttime temperatures, can significantly impact rice yields and grain quality, including milling properties and the incidence of chalky grains. For example, elevated temperatures can decrease rice yields and, when combined with rainfall during pollination, can lead to grain sterility (8). Elevated nighttime temperatures affect enzymatic activity during the grain-filling stage, disrupting the proper arrangement of starch. This leads to grain chalkiness, ultimately lowering head rice recovery (9). Fig. 1 illustrates the various constraints affecting rice production.

Production related constraints

The quality of rice is intimately linked to sowing time, which directly influences environmental conditions. Farmers must adjust their cropping calendar based on the preceding crop to ensure optimal sowing. Delayed sowing exacerbates high-temperature stress, resulting in decreased biomass, impaired grain filling, lower yields and compromised grain quality (10).

Sowing dates affects the cracking of rice during milling

Numerous studies to enhance paddy milling quality have highlighted cultivar selection and planting date as pivotal factors (11). The interaction between various plant characteristics and agronomic practices profoundly impacts a plant's ability to achieve optimal crop maturity and ease of harvest. These agronomic practices encompass planting date, seeding and fertilization rates (12).

Delayed planting exposes the grain to high levels of fissuring and cracking during harvesting, especially under adverse environmental conditions. Conversely, planting too early predisposes the grain to increased cracking due to immature kernels (13). By adjusting sowing dates, different varieties experience variations in heading and grain-filling temperatures, allowing assessment of their susceptibility to chalkiness. The temperature and chalkiness correlated most closely in the second week after heading and the first, second and fourth weeks after heading. Identifying the sensitive stage of grain filling is crucial in determining the best dates for sowing and heading rice varieties to reduce chalkiness through crop management practices.

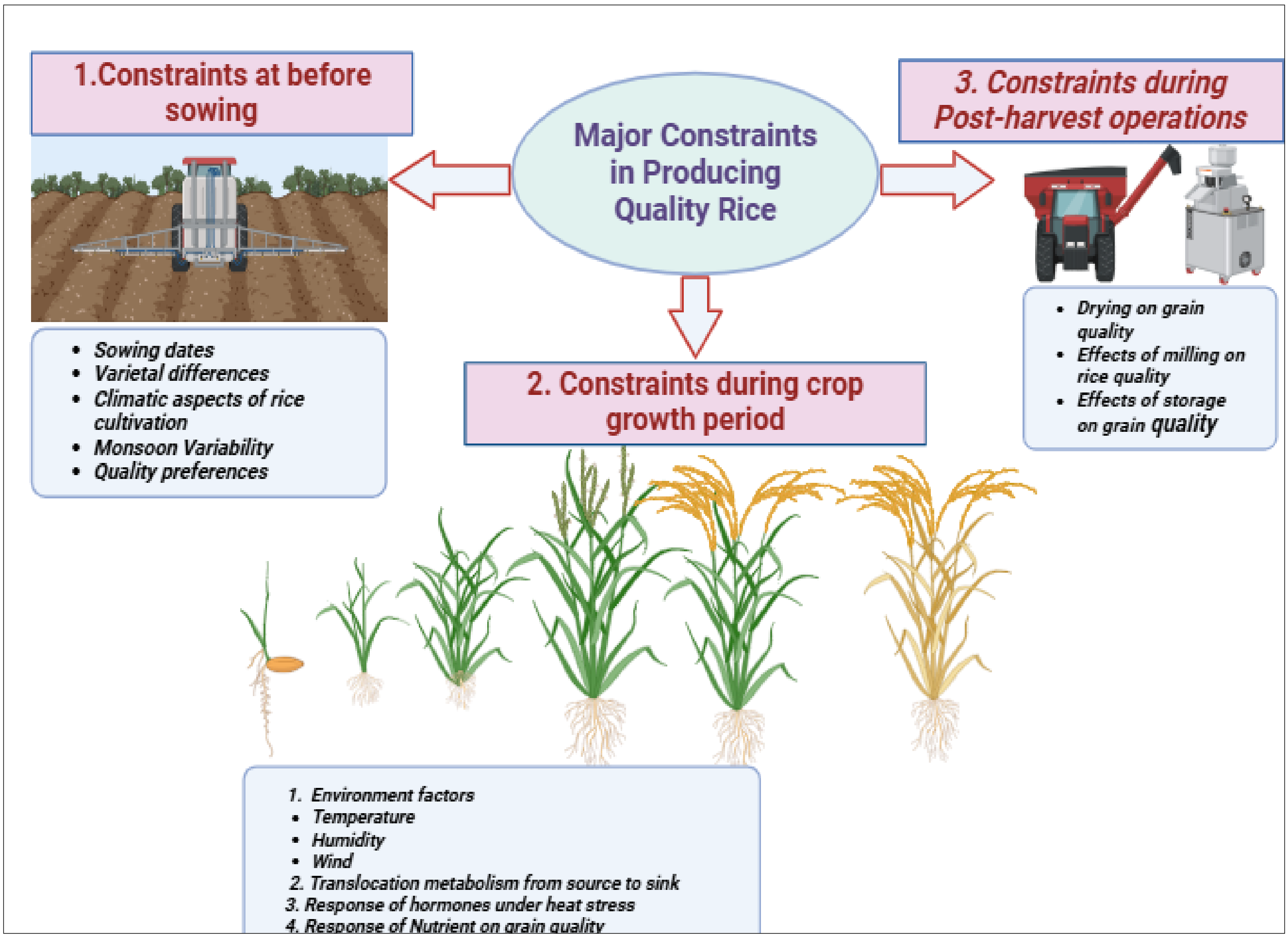

Fig. 1. Constraints and Factors Influencing quality rice production

Varietal differences

Varietal characteristics significantly influence the yield and quality of milled rice during the milling process. Milling outcome variations can be attributed to the different responses of different rice varieties to grain cracking due to their distinct genetic makeup (14). Understanding rice varieties, specifically their grain properties, makes implementing better management techniques easier, handling postharvest more effectively and maintaining better storage conditions. This will minimize losses during milling and preservation, improving overall quality in the process (15). Grain size and shape in paddy notably affect Head rice recovery. Slender grains generally more prone to breakages than medium and short grains (16). Pests and diseases like rice blasts or sheath blight may weaken kernels before harvest, deteriorating milling quality. The stink bug infests developing rice kernels, causing internal damage that manifests as a black spot (17).

Climatic aspects of rice cultivation

Rice (*Oryza sativa* L.) is the predominant rice variety globally, with its origins traced back to regions including India, China and Thailand. Rice production relies heavily on climatic factors cultivated in tropical climates characterized by high humidity, temperatures and abundant rainfall (18). In South and Southeast Asia, rainfall distribution emerges as a crucial determinant, while temperature and radiation assume greater significance in higher latitudes, notably in northeastern and northern Japan. Rice cultivation necessitates approximately 20 cm of water requirement per month during the wet season. Unique to rice farming is the practice of transplantation, typically performed about one month after sowing (19). This highlights the critical interplay between climatic conditions and rice production, emphasizing the need for meticulous management of environmental factors to ensure optimal yields of this vital food crop.

Monsoon variability

The correlation between rice yields, cultivation area, production and seasonal rainfall is powerful in India. In India, rice cultivation occurs primarily during two seasons: the kharif season, with planting between July and August and harvesting from October to January and the rabi season, where planting is done during the winter months (November-December) and harvesting is done between March and May. The availability of irrigation water during the dry season is significantly influenced by the rainfall received during the summer monsoon. As a result, variations in monsoon rainfall also impact rabi rice production, as Indian rivers are primarily fed by monsoon rains, with only limited contributions from snowmelt in northern regions. Monsoon rainfall generally benefits Kharif and Rabi crops, but September rainfall has a more significant impact on Rabi production. Kharif rice seems to rely more on local rainfall during the early stages of growth, whereas September rainfall in the Western Peninsula is particularly beneficial. For the Rabi crop, September rainfall across a substantial portion of the Peninsula emerges as the most critical factor influencing production (20). Rabi crops, while indirectly dependent on monsoon rainfall, benefit from a strong monsoon season (21). These crops are typically sown after the summer monsoon ends and mature during the spring or early summer (22). Seasonal rainfall during the monsoon season replenishes soil moisture, crucial for rabi crop growth during the post-monsoon period (23). Consequently, summer monsoon rainfall significantly influences crop production in India throughout the year, impacting both monsoon and post-monsoon crops (21). Intraseasonal variations in rainfall, characterized by alternating wet and dry spells, significantly influence the growth and yield of rainfed crops when considered in conjunction with the crop's phenological stages (23).

Constraints during harvest

In tropical regions, climatic patterns during the monsoon season might lead to delays in harvesting, while the lack of appropriate processing technologies can result in rice deterioration. Harvest timing ensures high-quality rice and optimal returns (8). Head rice yield is significantly influenced by the moisture content during harvesting. Harvesting at moisture levels higher or lower than optimal can lead to a reduction in head rice yield. As rice matures, the kernels on a panicle will have diverse moisture contents, indicating different stages of maturity and kernel strength (24). Typically, harvest timing is determined by various field factors such as crop size, harvesting capability and, particularly, weather conditions. Additionally, the field harvest approach aims to maximize both yield and quality of the harvested crop. Premature harvesting reduces yield and grain quality because immature grains are included, which results in poor milling performance. Conversely, delaying harvest can result in over-drying of the initial grains and potential exposure to environmental moisture upon rewetting, significantly reducing head rice yield (25).

Quality Preference

The quality of rice encompasses the characteristics of grains that meet specific consumer requirements and preferences for particular uses. Enhancing both paddy and edible rice yields requires advancements in breeding and improved agronomic practices. Simultaneously, as economic growth and living standards rise, consumer demand for superior grain quality is increasing. Grain attributes include a combination of physical and chemical characteristics that meet the specific requirements of different consumer groups for various applications. While preferences for certain quality traits may differ among countries and regions, the overarching trend toward enhancing grain quality persists (26).

Each type of rice grain is suited to specific agro-ecological conditions, known as its eco-geographic niche. Indica rice varieties are adapted to tropical environments, while japonica varieties thrive in temperate climates (27). Japonica rice, typically found in Japan, Korea and northern China, is characterized by short or medium grains with low amylose content. When cooked, it has a soft and moist texture. In contrast, indica varieties are common in tropical regions, with higher amylose content, resulting in firmer and drier cooked rice. The prevalence of indica or japonica grains varies across regions based on climatic conditions (28). While most rice consumed worldwide is non-glutinous, with amylose content exceeding 10 %, in Laos, where glutinous rice is a staple, most varieties have an amylose content of 10 % or less. In China, where indica varieties cover most rice cultivation area (28), the amylose content is similar to that of South and Southeast Asian rice varieties. In Thailand, most rice varieties have amylose content exceeding 20 %, with grains typically long and slender (29).

Postharvest operations on grain quality

Effects of drying on grain quality: Storing rice grains under high moisture conditions can lead to discolouration and increased susceptibility to pests, moulds and insects. The choice of drying method significantly influences rice's milling, cooking and eating qualities (30). Kernel fissuring during milling leads to grain breakage, reducing rice quality and market value. Fissures, fractures within the inner or outer layers of the kernel endosperm, increase the kernel's susceptibility to breakage (31). The occurrence of fissures may vary depending on the rice variety. Hence, proper drying and tempering strategies based on specific rice varieties are essential to minimize grain breakage and enhance milling quality (30). Key findings show the effects of drying on grain quality presented in Table 1.

Effects of milling on rice quality: Rice milling aims to produce edible grains by removing the husk and bran. Milling methods, duration, temperature and degree of milling significantly impact the quality of the final product. The milling quality and the chemical composition of the grain are determined by the milling equipment employed, the proficiency of the mill operator and the extent of milling. Rice colour significantly influences consumer perception and market value, with white rice, or fully milled rice, generally being more favoured. The observed colour variations in rice are determined by the amount of bran layers remaining on the kernel and the extent to which these layers are removed. These findings are summarized in Table 2.

The study found that most minerals are concentrated in the bran layer of rice kernels, whereas starch is primarily located within the inner core of the endosperm. The milling process significantly reduces the content of these nutrients. Lipids are also abundant in the bran layer and their concentration decreases as the degree of milling increases.

Effects of storage on grain quality: The quality of rice grains during storage is greatly influenced by endogenous enzymatic reactions affecting starch, proteins and lipids. These changes also vary based on storage factors such as temperature, humidity and duration. The primary objective of storing rice is to protect the grains from potential damage caused by factors such as excessive moisture, pests like birds and insects and microbial contamination, including bacteria. Optimal storage conditions help extend the shelf life of rice grains. The design and configuration of rice storage facilities depend on factors such as the volume of grains stored, the designed purpose of storage and the place of storage facility. Primarily, three key elements, moisture content, storage temperature and duration of storage, influence rice's physical, functional and chemical characteristics during postharvest storage. Table 3 shows effects of storage conditions on grain quality.

Environment factors influence the production of quality rice

Temperature: Grain-filling, the most critical stage for determining rice quality, is highly sensitive to temperature variations. During this period, the developing grain actively fills and accumulates essential substances like starch, protein and

Table 1. Effects of drying on grain quality

Milling quality	Findings
(32)	• Excessive moisture levels during harvest and controlled drying procedures result in paddy fissures, leading
(33)	• When kernels are dried to a moisture level of 15 % or lower, kernel fissures tend to increase as moisture is rapidly absorbed.
(34)	• Sun-drying on a concrete floor resulted in higher milling yields and fewer broken grains than drying on a mat. This is probably because sun-drying on concrete takes longer to achieve the desired moisture content.
Appearance quality	
(35)	• Temperature significantly influences the discolouration of rice grains, where prolonged drying at high temperatures leads to yellowing of the rice.
(36)	• Grain drying at temperature >50° C for more than 12 hr causes colour degradation and yellowing.
Cooking and eating quality	
(37)	• The key components of rice that influence its taste include protein, starch, lipids and moisture. • As rice ages, chemical transformations occur, such as converting neutral lipids into fatty acids, resulting in an undesirable odour. • Higher drying temperatures during paddy processing lead to elevated levels of fatty acids in rice. To maintain the taste quality of rice, it is recommended to dry paddy at temperatures below 45°C, as
(38)	• Paddy rice drying at a high temperature (at 130 °C or 150 °C) may increase the head rice yield, which may be due to the partial gelatinization of starch.

Table 2. Effects of milling on quality

Reference	Findings
(39, 40)	• Colour intensity and the lightness value of different rice varieties increase as the increase in degree of milling.
(41)	• The extent of milling impacts the composition of different compounds, including sugars, amino acids, vitamins and minerals.
(39)	• Rice predominantly consists of carbohydrates, with minimal protein, minerals, fats and other components. • Approximately 84.2 % of the protein in rice kernels is found in the outer endosperm layer and this protein concentration decreases further during the milling process.
(42)	• Rice milling at lower degrees is less adhesive and cohesive (Water uptake and length expansion of rice). • These grains are harder and require more cooking time, yielding smaller volumes and less length expansion than rice milled to a higher degree.

lipids, ultimately defining the rice's key quality attributes (50). High night temperatures reduce grain quality, leading to lower head rice yield, increased chalkiness and reduced grain width (51). complex polygenic traits of rice such as chalkiness, amylose content, protein content, grain length, grain width and aspect ratio, are significantly influenced by components like light, temperature, humidity and specific cultural practices during grain filling (52). Both genetic and environmental factors significantly impact the quality of rice grains, particularly photoperiodism and temperature during the heading and doughing stages. Because of the high temperature during the heading stage, there is a decreased head-rice ratio and an increased occurrence of chalky grain (53). About 25 °C is the ideal temperature for producing rice of the highest caliber during the filling stage (54). High temperatures during the grain filling and dough stages reduce carbohydrate accumulation in kernels, decreasing head rice yield and cooking quality. This is the cause of the degradation in rice quality (55) and the findings of climatic factors that influence the quality of rice are shown in Table 4.

Cool temperatures: Cold injury is a major abiotic constraint that limits the yield potential of rabi rice. During the vegetative phase, cold injury can manifest as reduced germination, slow seedling growth, leaf yellowing and stunted growth characterized by reduced plant height and tiller number. Temperatures below 18 °C from primordial initiation to the maturity phase can adversely affect anthesis and pollination, leading to delayed heading, incomplete panicle exertion, prolonged flowering and spikelet sterility (both complete and partial), ultimately reducing yield. The severity and duration of the cold period directly correlate with the extent of cold injury. Furthermore, high humidity in conjunction with low temperatures before flowering increases the incidence of spikelet sterility (56).

Congenial temperature: Rice, being a tropical and sub-tropical crop, thrives in temperatures ranging from 20 °C to 40 °C. Optimal germination, with a rate of 90 % or higher, occurs within approximately 6 days at temperatures between 15 °C and 37 °C, while no germination occurs at 8°C and 45°C. Temperature also influences the leaf emergence rate, with leaves typically emerging every 5 days at 20°C and every 4 days at 25 °C before panicle initiation. The tillering rate tends to increase with rising temperatures, with a suitable temperature of 25 ^{0}C to 31 ^{0}C for tillering. Similarly, ripening temperatures are between 20 °C to 25 °C. Critical temperatures for inducing spikelet sterility vary from 10 °C to 15 °C (59). The suitable temperature for producing high-quality rice is about 25 ^{0}C at the grain filling stage (60).

The ideal temperature range for rice ripening is 20-25 °C. A decrease of 1 °C in the minimum temperature during the dry season growing period can result in a 10 % reduction in grain yield, while the impact of maximum temperatures on yield is negligible. Increased night temperatures can significantly decrease rice yields (61). Paddy rice is typically harvested at around 20-25 % moisture content. The quality of rice is influenced by both the cultivar and growing environment, particularly temperature during ripening. Adjusting sowing dates is a common strategy to improve the quality of rice and optimize temperature (62).

Humidity: Rice cultivated in submerged conditions creates a high relative humidity environment, essential for its growth. An ideal relative humidity (RH) of 80-85 % promotes shoot growth in rice. Research shows that the photosynthetic rate of rice increases as humidity rises, particularly at temperatures of 22 °C, 28 °C and 34 °C. A positive correlation exists between humidity levels, leaf temperature and stomatal aperture in the upper canopy. (62). The minimum RH required for rice flowering is 40 %, with an optimal range of 70-80 %. However, excessive humidity during this phase can decrease yields (63). In regions with high temperatures and low RH or low temperatures and high RH, the glumes may fail to open, resulting in poor pollen viability (64) and reduced spikelet fertility with increasing RH. (65). RH affects the transpiration rate. An increased rate of transpiration may impact the physiological process. Higher relative humidity accelerates transpiration during the reproductive phase, ultimately reducing yield (64).

Table 3. Effects of storage conditions on grain quality:

Reference	Findings
(43)	• During storage, several physiological changes occur, including pasting properties, colour, flavour and composition that affect rice quality.
(44)	• Discolouration of rice is accelerated at slower rates when the rice varieties are stored at a lower temperature.
(45)	• Postharvest storage, as red rice often changes to a darker reddish brown colour, alters preexisting chemical components, notably reducing polyphenol content and oxidative degradation of proanthocyanidin pigments.
(46)	• Higher moisture content levels during storage result in a higher percentage of discolored kernels in rough rice.
(47)	• The storage of rice under elevated temperatures leads to a notable increase in hardness and a decrease in adhesiveness compared to storage at lower temperatures.
(48)	• The flavor components of cooked rice undergo rapid changes during aging, with carbonyl compounds, particularly hexanal, believed to be the primary contributors to off-flavors as they accumulate during storage.
(49)	• The storage-induced changes in the thermal properties of rice may be attributed to alterations in the cell wall structure and protein characteristics during the storage period

Table 4. Climatic factors influence on quality of rice

Parameter	Element	Impact	Scientist
Milling rice and Head rice yield	Elevated CO2	Increasing in milling rice recovery by 10.7 % but reduction in head rice yield by 13.3 %	(57)
Immature chalky grains		insufficient assimilate supply leads to an increase in immature chalky grains.	(58)
Protein content	CO_2	Increased levels of carbon dioxide (CO2) can lower the grain protein content of rice, thereby enhancing its eating quality but not its nutritional quality.	(57)
Rice Quality	Temperature	Deterioration of rice quality observed under elevated temperature	(54)

Wind: The period from active tillering to heading, there was a notable inverse relationship between wind speed and both the number of panicles per plant and straw yield (66). Optimal paddy harvesting typically occurs at moisture contents between 20-25 %. A gradual drying process from these levels to approximately 14 % moisture content, which is ideal for milling, minimizes fissuring and breakage during the milling process (67). Table 5 illustrates how variations in weather elements beyond normal ranges during various phenological phases of crops can significantly affect grain quality. These abnormal conditions can disrupt key growth processes and diminish grain quality.

Optimum Sowing Time for Rice Crop

Planting time is a key factor in crop productivity, varying based on location and climatic conditions. To maximize yield potential, it is imperative to subject the rice crop to the most conducive temperature range, achievable through strategic sowing practices (77). Sowing date adjustments influence temperature and daylight exposure, significantly impacting crop development and dry matter distribution. Under southern Alpine conditions, the duration from transplanting to maximum tillering is reduced with delayed transplanting dates (78). Delayed transplanting significantly impacted the timing of flowering, delaying the onset of both 50 % and 100 % flowering (79). Furthermore, later sowing dates delayed the initiation of young panicle differentiation and subsequent heading dates (80).

The age of seedlings upon transplanting significantly influences the uniformity of rice stand establishment. Seedlings exceeding the optimal age exhibit reduced tillering due to a truncated vegetative period, resulting in diminished yields. Among the factors impacting crop production, the timing and method of sowing serve as crucial prerequisites for ensuring the timely and successful completion of a crops' life cycle within a specific agro-ecological context. (81). The milling quality of rice decreased when planted either before or after the optimal planting window, highlighting the importance of selecting cultivars with high and consistent milling yield potential for these planting dates (82). A significant increase in the percentage of bran and decrease in amylose content is observed in delayed sowing. The cooking time is impacted by late transplanting dates, which shorten the cooking time but increase solid gruel losses. Similarly, late transplanting had higher clearing and spreading values, worsening the cooked rices' organoleptic characteristics (83).

High-Temperature Influence on Translocation Metabolism from Source to Sink

The source-sink relationship and rice plant traits influence the extent of assimilate translocation during grain filling (84). Studies on source-sink relationships have revealed a link between assimilate supply and chalky core formation (85). Increasing assimilate supply can reduce chalkiness, even under high temperatures (86). High night temperatures increase respiration rates during darkness, reducing carbohydrate reserves available

Table 5. Effect of weather elements at different crop stages leads to poor-quality grain

Weather element	Stage of impact	Findings	References
Temperature/ Heat stress	Flowering	• The average temperature under 20 °C for 5 days during flowering increased the probability of obtaining spikelet sterility by greater than 10 - 12 %.Temperature and sterility were observed to have a negative correlation, which indicated that lower temperature induced high sterility.	(68)
	Heading	• Under elevated temperatures, grain thickness in rice was reduced most by high temperatures, which began 12 days after heading. Still, grain length and width were most sensitive to high temperatures at the early stages of development.	(69)
	Early grain filling	• High temperatures starting 12 days after heading had the most significant impact on reducing grain thickness in rice. However, grain length and width were most susceptible to high temperatures during the early stages of development.	(70)
	Heading stage	• Increased probabilities of chalky grain occurrence and decreased head-rice ratio.	(71)
Humidity	Flowering	• Increasing humidity results in increased Leaf temperature and stomata aperture in the upper part of the canopy.	(63)
		• The flowering is inhibited at RH is <40 %.	(72)
		• The duration of lemma closure in rice declined as relative humidity rose from 60 to 100 percent. Relative humidity plays a role in determining the rate of transpiration. The increased transpiration may influence the physiological process, affecting the yield.	(73)
		• With increasing RH, Spikelet fertility was reduced.	(64)
Wind	Flowering	• Intense wind causes sterility at flowering by desiccating the plant	(74)
		• Examination of the reproductive organs revealed the absence or dehydration of both anthers and ovaries, attributed to wind speeds ranging from 43 to 48 kmph.	(75)
		• Pollen dehydration and spikelet sterility in rice caused by high wind speed at the flowering period.	(76)
Solar Radiation	Flowering	• Decreased light exposure during flowering decreases levels of auxins and cytokinins while increasing gibberellins in the spikelets. In conditions of low light, there is a reduction in proline content within the panicle and an increase in proline content in the leaf and culm, particularly in varieties susceptible to shade. • The diminished proline content in the panicle is attributed to both impaired translocation and increased proline oxidation, which is influenced by carbohydrate depletion in shaded conditions. The insufficiency of proline in the spikelets may also contribute to increased sterility.	(77)

for grain filling. Numerous studies have shown that temperatures exceeding critical thresholds, such as 33 °C or 35 °C, can negatively impact rice yields by affecting spikelet fertility, shortening grain filling duration, reducing grain weight and compromising grain quality (87). High-temperature stress during the Early Panicle Initiation (EPI) stage impairs grain weight development by reducing non-structural carbohydrate reserves, hindering vascular bundle development and limiting grain size, including Longitudinal dimension and Broadness. (88) This grain weight reduction results from decreased carbohydrate allocation before flowering, limitations in assimilate flow and alterations in source-sink relationships, which directly impact spikelet development, including glume formation and grain size, consequently reducing overall grain weight and yield (89). High-temperature stress at the EPI stage hinders spikelet differentiation, promotes the occurrence of degenerated spikelets and disrupts nitrogen distribution, further contributing to decreased grain weight (89). Changes in the arrangement of starch granules may occur due to decreased dry matter in panicles due to high-temperature stress. Furthermore, the insufficient supply of assimilates to grains during heat stress conditions has been proposed as a factor contributing to the formation of chalky grains. (89).

Response of Hormones under Heat Stress

The regulation of rice spikelet differentiation involves a range of hormones, such as IAA, cytokinin (CTK) and ABA (90). Plant hormones are instrumental in governing grain formation. For instance, IAA plays a crucial role in influencing rice grain morphology by stimulating the growth and maturation of both glume and endosperm cells (91).

Response of Nutrient on Grain Quality

Nitrogen fertilizer impacts rice grain quality, including milling and nutritional aspects, as highlighted by studies (92). Grain nitrogen content correlates with plant nitrogen uptake. Excessive nitrogen increases protein content but reduces cooking and eating quality (93). Furthermore, exposure to high-temperature stress during the cultivation of rice and Post-flowering reduces nitrogen allocation to grains while maintaining sufficient allocation to vegetative organs for optimal photosynthesis and yield (92). Elevated temperatures also elevate grain nitrogen concentration due to heat stress's greater impact on rice grains' carbon accumulation than nitrogen (93).

Identification of Optimum Weather Conditions and Time of Sowing Window on spatial scale (tools/models)

Beyond soil quality, a region's agricultural suitability is heavily influenced by its climate. Precipitation is the primary determinant of water availability in rainfed agriculture and plays a significant role in irrigated systems. Temperature exerts considerable control over the duration and timing of plant developmental stages, ultimately impacting crop productivity (94). With the onset of climate change, the climatic conditions during the growing season are anticipated to shift (95). Adaptation strategies are necessary to address these evolving climatic conditions, such as adjusting sowing times (96).

Crop growth models are valuable tools for predicting global crop productivity and are increasingly used worldwide (97). Essential inputs for these models include weather data and information regarding management practices, such as crop selection, variety types and sowing time. Global circulation models (GCMs) typically provide the source of future weather data for global crop growth models. Farmers are likely to adjust sowing schedules in response to climate change, altering current planting patterns (98).

Existing crop models employ various methodologies to determine both current and optimal sowing dates. For example, models like LPJmL assess sowing dates based on

Table 6. Different models are used to identify weather conditions and the time of sowing window on the spatial scale in different crops.

Study	Objective	Crop(s)	Tool/model used	Spatial scale	Key findings
(101)	Evaluate the effect of sowing dates and define optimal sowing window	Wheat	CERES (Crop Environment Resource Synthesis)-Wheat model	Regional	Optimal sowing window 20 Nov - 5 Dec gave the highest yields
(102)	Simulate the impact of temperature on maize development	Maize	SSM-iCrop model (Simple Simulation Model)	Sub-regional	Cardinal temperatures for phenology established, enabling prediction of optimum sowing window
(103)	Determine agro-climatic suitability for chickpeas across districts	Chickpea	CLIMEX (Climate Index Model for Exploring) model + GIS	District level	Suitability maps created; optimal sowing Nov 1st week for most locations
(104)	Elucidate quantitative response of wheat varieties to sowing dates	Wheat	CERES-Wheat model + GIS	Regional	Significant genetic variability was observed in response to sowing dates
(105)	Optimize potato sowing windows using weather variability analysis	Potato	Optimization model	State level	Optimized sowing windows generated spatially for major potato-growing areas
(106)		Rice	InfoCrop (Information on Crop) + GIS	State level	Sowing date maps were created; yield losses were prevented through identified optimal windows.
(107)	Predict best sowing & maturity dates for cotton using temperature effects	Cotton	DSSAT (Decision Support System for Agrotechnology Transfer Cropping Systems Model) -CSM (Cropping System Model) model	Regional	Optimized cotton calendars significantly increased lint yield over farmers' calendars.
(108)	Develop open access decision support platform for optimizing maize sowing dates	Maize	AgTrials + mobile app	Farm level	Allowed site-specific optimal sowing dates recommendations to farmers

climate data and crop-specific water and temperature requirements (97). Alternatively, models like DayCent (99) optimize sowing dates within the model to maximize crop output, while other models, such as GAEZ, identify the optimal growth period based on predefined crop-specific criteria (100).

In contrast to fixed sowing dates, utilizing climate data to determine and optimize sowing dates provides the flexibility to simulate the effects of future climate change on sowing schedules. However, the results for optimization methods heavily rely on the specific crop model employed, thereby introducing additional uncertainties to the results. Table 6 presents the different models to identify weather conditions and the sowing window time on various crops' spatial scales.

Conclusion

Rice production, heavily concentrated in Asia, faces multifaceted challenges influenced by climate variability, environmental factors and agronomic practices. The impact of precipitation patterns, particularly during the summer monsoon season, significantly impacts Kharif and Rabi foodgrain yield, with variations affecting water and soil moisture availability across India. It underscores the urgent need for adaptive strategies when coupled with rising temperatures and CO_2 levels. Optimizing sowing schedules, improving postharvest management and integrating advanced crop models with weather data can enhance resilience in rice cultivation. Additionally, maintaining grain quality requires a holistic approach, considering genetic traits, environmental influences and storage conditions. Moving forward, targeted research and policy interventions must focus on climate-resilient varieties, sustainable agronomic practices and technological innovations to secure rice production and global food security in the face of ongoing climate challenges.

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Authors' contributions

MB contributed to conceptualization, data curation and formal analysis. RK was responsible for supervision, project administration and manuscript review and editing. BN handled funding acquisition, methodology development, validation and original draft writing. GD contributed to the investigation, software application and original draft preparation. KB provided resources, managed data visualization and assisted in project coordination. DV was involved in experimental design, methodology and manuscript review and editing. MK and GR carried out the literature review and critical revision of the manuscript.

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