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REVIEW ARTICLE

Comprehensive insights into the risks of climatic factors on rice production and its value chain- A Review

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Abstract

Climate change is the most serious problem of the last two centuries. It is being observed as a silent threat to global food production, leading to food insecurity for the burgeoning population. Rice is an important food crop and has also been identified as sensitive and highly vulnerable to climate change. Global rice production is affected by climate change and will soon be seen as a food security threat. Climatic factors like temperature, rainfall, wind speed, relative humidity, and solar radiation significantly impact physiological, biochemical and morphological traits, eventually resulting in a decline in yield. The whole process is discussed in this review. Several previous studies focused more on the impact of climate change on the productivity and production of crops without paying any or less attention to the vulnerability of value chain actors to climate risks and climate-related losses in the value chain. The climate risk management by value chain approach establishes connections between input suppliers, farmers, processors, retailers and consumers, identifying risks and formulating adaptation and mitigation strategies at every stage across the value chain. The identified appropriate strategy from the review, including climate-resilient rice varieties, conservation agricultural practices, climate-smart cultivation and water management techniques, could reduce the impact of climate change and enhance food security.

Keywords

climate change; climate risk; rice production; value chain approach

Introduction

Global climate change has increased the earth surface temperature, which is expected to rise by 2 to 4°C by 2050 (1-3). Extreme climatic events, namely floods, cyclones, droughts and heat waves, harm global socio-economic, biophysical and ecological systems (4-9). Many countries worldwide are anticipated to experience rising temperatures and changes in the distribution of rainfall over the seasons, as well as an increase in the frequency and intensity of extreme weather events (10-14). Extreme weather conditions are consequences of climate change, which consequently induces anxiety globally due to its threat to agriculture and food security (15-19). No sector is more susceptible to climate disasters and catastrophic weather phenomena than the agricultural sector. Since weather conditions, such as rainfall and temperature, serve as a direct input to the crop sector, any change and fluctuation in these variables will significantly impact crop yields in terms of quality and quantity (22,23). It may also expose people to problems of food insufficiency, food insecurity and poverty. Despite beneficial effects like enhanced CO_2 for short-term gain, a still severe decline in some crops due to adverse weather has been reported by several researchers (18, 24).

Rice is one of the most essential stable crops in the world, as half of the worlds' population consumes rice daily (24-29). The slogan "Rice is the Life '' is most appropriate for India, as this crop plays a vital role in our national food security and is a livelihood for millions of rural households (30). Rice supplies 20% of the worlds' dietary energy, while wheat and maize supply 19 and 5%, respectively (31). According to the Global Rice Science Partnership, rice provides over 70% of the calorie supply in some Asian countries (32). However, rice is considered one of the most strategic commodities in the world; it is not only linked with global food security but also closely connected with economic growth, employment, social stability and regional peace (33). It has also been identified as a crop, vulnerable to climate change due to its sensitivity to changes in weather conditions (24, 26, 34-36). According to 2023-2024 statistics, China leads in rice production with 28% of world production, followed by India (26%), Bangladesh (7%), and Indonesia (6%). China holds the leading position in global production with 144.62 million metric tons, followed closely by India, which produces 137.83 million metric tons. Bangladesh contributes 37 million metric tons, while Indonesia adds 33.02 million metric tons to the global output. Vietnam produces 26.63 million metric tons, rounding out the list of top producers. Together, these countries form a substantial portion of the worlds' production output. Researchers estimate that rice and other crop production will need to increase by more than 70% to meet the dietary demands of the world's fast-expanding population by 2050. This increase in production is required to avoid food shortages and disasters.

An agricultural value chain establishes connections between input suppliers, farmers, processors, retailers, and consumers (37). International Fund for Agricultural Development (IFAD) has reported that "some agricultural value chains may no longer be economically viable over periods of as little as 20 years, as climate change pushes beyond the thresholds of crop, pasture or fisheries suitability in the areas of production" (38). Climate change is causing decreased rainfall and water scarcity, flooding, and rising average temperatures, all of which strain domestic rice value chains. The effects of climate change are expected to exacerbate value chains in the future. Extreme weather and climatic variability pose potential risks to rice value chain actors (RVCAs) since they are interrelated and have a ripple effect throughout the rice chain. A sustainable and effective rice value chain can only be achieved by collaborating with all RVC stakeholders to mitigate climate risks (39).

Climate risk management is highly imperative to facilitating the efficient operation of the value chain. Climate resilience must be the primary objective for value chain development efforts to have a lasting effect on food security and poverty reduction. All players in the value chain must be aware of climatic risks and equipped to handle them to achieve a climate resilient value chain continuously. The present review discusses the (i) Impact of climatic factors on rice production (ii) the impact of climate risk on other parts of the rice value chain (iii) Adaptation measures to mitigate climate risk in the rice value chain.

Methodology for literature collection

The search utilized databases including Google Scholar, Scopus, and Consortium For e-Resources in Agriculture (CeRA). The search string used to collect information was outlined as: ("Climate AND Rice", "Rice" AND "temperature", "Rice" AND "Rainfall", "Rice" AND "Value chain", "Climate" AND "Rice" AND "value chain", "Rice" AND "Climate" AND "Adaptation", "Rice" AND "Climate" AND "Mitigation"). Articles must provide quantitative results about at least one aspect of climate risk in rice production or the rice value chain to be included in the current review. Other important articles felt to be necessary for this review are also added. The framework of the literature collection is given in Fig. 1. The articles are available with full text written in English language and articles relevant to our three focus areas of review that were selected for the study. However, the studies with abstracts, repeated articles and other languages that were irrelevant to our scopes were rejected. This study, 1129 articles were found with those keywords in various databases, of which 214 duplicates were removed. After that, 691 articles with abstracts and other languages were excluded. From 224 articles, the articles that fall under any three aims of the review were screened and finally, 115 articles were selected for the review.

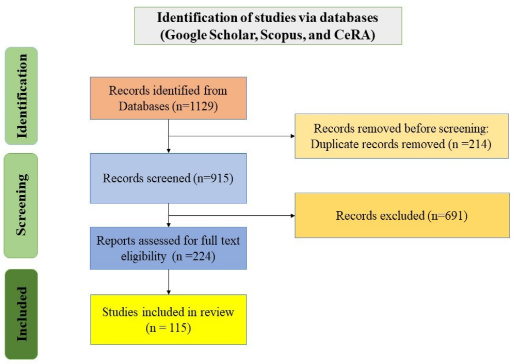

Fig. 1. Framework of the literature collection for review

Global rice production scenario

The Intergovernmental Panel on Climate Change (IPCC) in their sixth Assessment Report (40) on Climate Change, has emphasized that 10% of the land suitable for cultivating food crops would be climatically unfit by the middle of the century with a high-emission scenario (SSP 585). Global concern over climate variability, change and its effects and vulnerabilities are rising. Rice is being cultivated in both irrigated and rainfed conditions; however, the former constitutes 75 per cent of global rice production, demonstrating the relevance of irrigated rice to global food security (41).

According to US Department of Agriculture (USDA), rice ranks third globally in terms of production, following maize and wheat (Fig. 2) and China ranks first in milled rice production, followed by India and Bangladesh (Fig. 3). The 15 million hectares of land were used worldwide for rice cultivation in 1961 (31). Between 1961 and 2019, the regions of the globe that cultivated rice increased by more than 40% and during this period, rice production tripled, reaching 755 million tonnes and the majority of this production came from Asia. Together, the seven Asian countries *viz*., China, India, Indonesia, Bangladesh, Vietnam, Myanmar and Thailand produce more than 80% of the world's rice production. The largest increase in rice farming areas across all continents was observed in Africa, whereas South America expanded by around 3.5%. Africa is one of the places where rice production has developed the fastest almost ninefold, with Egypt, Nigeria, and Madagascar being the top producers. Globally, India ranks first with approximately 44 million hectares under paddy cultivation (42). The significant paddy production losses of 5.39, 12.44 and 3.87 percent will occur in China, Bangladesh, and Myanmar, respectively, with a 1.5°C increase in temperature (43). Changes in temperature and precipitation due to global warming have been noticeable in many regions

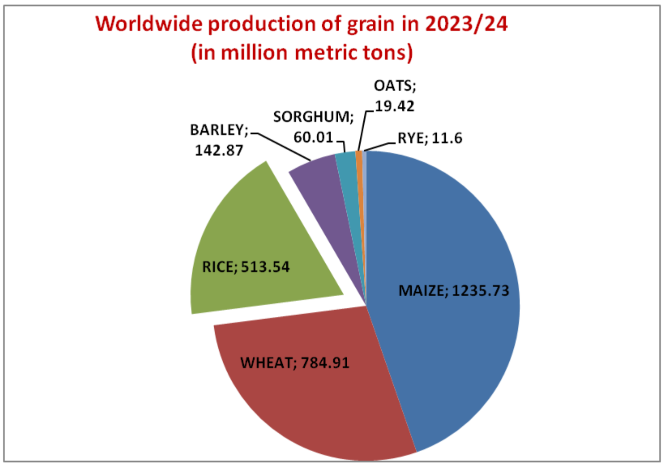

Fig. 2. Worldwide production of food grains in 2023-2024 (Data Source: US Department of Agriculture)

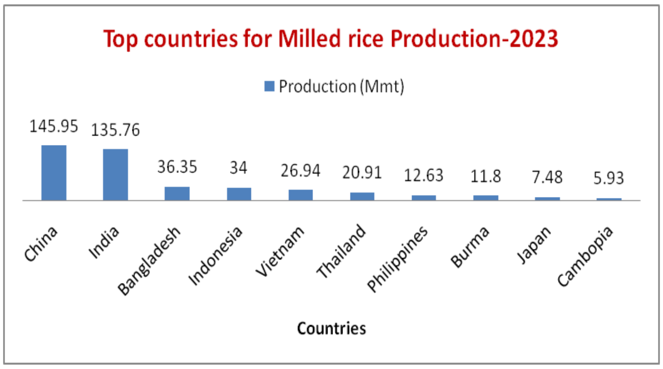

Fig. 3. Top Countries Milled Rice Production in 2023 (Data Source: US Department of Agriculture)

of the world. It is made worse by the fact that India is experiencing more fluctuation in its climate than ever before (44). Rainfall patterns are unpredictable and have an unequal temporal and geographical distribution which can lead to floods or extended dry periods that mimic drought conditions.

Impact of climatic factors on rice production

Climatic factors such as temperature, wind speed, solar radiation, relative humidity and rainfall, affect crop production directly or indirectly (28, 45-49). The different weather calamities, namely rainfall, temperature, relative humidity and rice productivity in the Aceh Besar region in Indonesia, affected rice growth, development and yield (50). The major key findings by various researchers is summarized and presented in Table 1. Saravanakumar found that rainfall and temperature significantly impact rice yield in Southern India (45). Crop development is also influenced by wind speed and relative humidity (51). The critical meteorological factors associated with each rice phenological stage, regulating the growth and productivity of irrigated rice are shown in Fig. 4. Among the parameters rainfall and temperature affect the yield much and RH with temperature slightly influences the yield. Wind speed causes mechanical damage and the intensity varies with the crop's stage encountering high wind speed.

Table 1. Summary of key findings regarding climatic factors' impacts on rice production

Climatic Factor	Key findings	Reference
Temperature	Extreme temperatures during the blooming stage reduce cereal kernel count, thickness and quality	(52)
	Germination was hindered by a temperature of 35°C or above	(53)
	Flowering stage is the most vulnerable to cold damage	(58)
	Temperature of 19°C creates sterile grains	(59, 60)
	Low temperature reduces photosynthetic activity.	(51)
	High night temperature (HNT) increases spikelet sterility, thereby decreasing pollination.	(26)
Rainfall	Rainfall rises by 5 or 15%, yield is reduced by 5.71 and 15.26%,	(62)
	Rainfall during the maturity stage has an adverse influence	(47,64)
	Flooding during the vegetative development stage leads to a 40 per cent reduction in rice production.	(66)
	A rainfall of 100 mm ha^{-1} during the flowering stage increases in chaffy grain	(48)
	Rainfall also brings preharvest sprouting and impacts rice during the ripening stage.	(70,71,72)
Relative Humidity	High rice sterility was observed when the relative humidity reached above 85% along with the temperature greater than or equal to 35°C	(59,75)
	Flowering is impeded if the relative humidity falls below 40%	(76)
Solar Radiation	The best conditions for achieving the highest grain production are cumulative solar radiation of 14,000 g cal cm^{-2} and 200 hours of sun exposure 30 days before harvest.	(79)
Wind Speed	Rice culms break at wind speeds of around 7 m s^{-1}	(68)
	Winds above 4 ms^{-1} impeded rice fertilization	(82)
	Wind speed ranging from 9.7 to 11.11 m s^{-1} during flowering was responsible for 25.7% of the reduction in grain production and 77.3% of the unfilled grain.	(48)

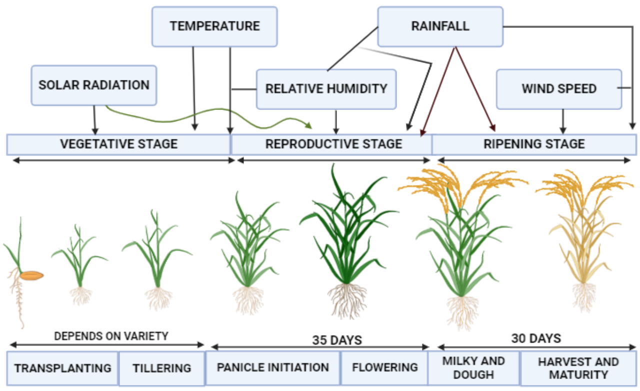

Fig. 4. The Flow chart represents the crucial meteorological factors associated with each rice phenological stage that determine the growth and productivity of irrigated rice.

Effect of temperature on rice

Temperature and radiation are two key environmental factors directly or indirectly impacting rice yield (49). Extreme temperatures during the blooming stage reduce cereal kernel count, thickness and quality (52) and increase temperature, reducing yield by reducing the grain filling period (3). Rice requires a temperature between 20 and 40°C for its growth and development and the stage-wise cardinal temperatures are given in Table 2.

Table 2. The critical rice temperature in various growth stages is summarized in (55).

Growth stages	Critical temperature (°C)		
	Low	High	Optimum
Germination	10	45	20-35
Tillering	9-16	33	25-31
Panicle initiation	15	-	-
Anthesis	22	35	30-33
Ripening	12-18	30	20-25

Low temperatures in temperate zones and high temperatures in lower tropic elevations harm crops. Due to a high respiration rate, germination was hindered by a temperature of 35°C or above (53). The optimum temperature ranges for rice from 30 to 32°C, but, it is 22-31°C. The Yangtze River Valley's temperature extremes were analyzed using long-term meteorological data trends, demonstrating how sensitive rice productivity is to temperature changes throughout the reproductive stage (53, 55, 56,). Based on his research, he hypothesized that the province's ability to cultivate rice is probably impacted by the rising night and daytime temperatures and fertilization begins to disappear at higher temperatures. The temperature variations resulted in a decline in the quality of yields and increased insect and disease attacks (57).

On the other hand, all phenological phases of rice are impacted by cold conditions, which also reduces grain yield and productivity. Germination, booting, flowering and filling periods are sensitive to cold damage and the flowering stage is the most vulnerable to cold damage (58). A temperature of 19°C creates sterile grains (59, 60). Since low temperature reduces photosynthetic activity, they have a negative effect on the dry matter of seedlings (51). Low temperature restricts the pace of tillering, and they also lengthen the tillering period, producing more tillers and panicles than at high temperatures and the lower temperature increases sterility (53, 61). Studies in northern Italy, Japan and Korea also indicated a high grain sterility rate due to the average nighttime low of 11°C during summer (62). High night temperature (HNT) increases spikelet sterility, decreasing pollination (26).

Effect of rainfall on rice

The anticipated rice output would decrease by 5.71 and 15.26%, respectively, if rainfall increased by 5 or 15% throughout the growing season (63). Rainfall during the maturity stage adversely influences rice yield (47, 64). In India, the variance in rice yield during the monsoon season was positively connected with intense rainfall (65). As a result, rice production will be less reliable in a climate with more intense precipitation. Rainfall has varying detrimental effects on rice production based on the stage of development. According to flood assessment data, Flooding during the vegetative development stage reduces rice production by 40% (66). Raindrops and the weight of the precipitation create lodging in rice, resulting in a decline in rice production (67-69). In addition, the rice crop is particularly susceptible to lodging during the grain-filling stage due to its centre of gravity (70). A 100 mm ha^{-1} rainfall during the flowering stage (48) resulted in a 55.7 to 182.3% increase in chaffy grain. Rainfall also brings preharvest sprouting and impacts rice during ripening (70-72).

Effect of Relative Humidity on rice

The ideal relative humidity range for rice cultivation is 60 to 80%. Relative humidity significantly influences rice production from transplanting to blooming (73). Temperature affects relative humidity and there is always much more moisture in the atmosphere in the morning than in the afternoon. When rice is grown in standing water, a high relative humidity environment is created (51). RH appears to have indirectly influenced pollen viability under greater air temperatures, as evidenced by enhanced pollen viability and pollen deposition on the stigma with decreased spikelet surface temperature (74). Because of this, rice's pollen viability, anther splitting, pollen shedding and spikelet sterility are all influenced equally by air temperature and humidity. High rice sterility was observed when the relative humidity reached above 85% and the temperature greater than or equal to 35°C, considered a critical threshold (59, 75). In addition, a minimum of 40% relative humidity was needed, with 70 to 80% being the ideal range during the flowering stage and flowering is impeded if the relative humidity falls below 40% (76).

Effect of Solar Radiation on Rice

The light intensity greater than 1200 moles $m^{-2}s^{-1}$ (or) 100000 lux helps in better production, resulting in tillering, growth, biomass and rice yield. In the vegetation stage, tillering is reduced by low light intensity because of less photosynthates production. The amount of daylight received during tillering showed a substantial positive link with grain production (77). Tillering typically benefits from a long vegetative phase and intense radiation throughout this period. During the reproductive stage, the low light intensity during Kharif limited tillering and dry matter production in contrast to the rabi season (78). According to (79), the best conditions for achieving the highest grain production are cumulative solar radiation of 14,000 g cal cm^{-2} and 200 hours of sun exposure

30 days before harvest. The intense cloud cover throughout the tropical regions means there are only 3 to 4 hours of good sunshine daily and the region records meagre rice productivity (1.5 - 2.5 t ha^{-1}) (51).

Effect of Wind Speed on Rice

Of all the abiotic stressors, extreme winds and drought result in the highest losses (57,69). Generally, strong winds impact specific growth seasons and rice culms break at wind speeds of around 7 m s^{-1} (68). Rice was lodged due to the severe wind shattering the culm, significantly decreasing yield (80). In Japan, a breeding program was started to find a rice variety resistant to lodge to prevent rice lodging caused by typhoons, and they found that max windspeed significantly influences typhoon damage events in which the average max windspeed value (5.55 m s^{-1}) was less than 7 m s^{-1}(81). Winds above four metres per second impeded rice fertilization (82). There is a substantial correlation between grain yield and wind speed (83). Grain maturity and development were shown to be poor during severe winds. Furthermore, wind speed ranging from 9.7 to 11.11 m s^{-1} during flowering was responsible for 25.7% of the reduction in grain production and 77.3% of the unfilled grain (48). Elevated wind speed during blooming led to pollen dehydration, resulting in rice spikelet sterility (84).

Climate Risks in the Rice Value Chain

Several previous studies focused more on the impact of climate change on the productivity and production of crops without paying any or less attention to the vulnerability of value chain actors to climate risks and climate-related losses in the value chain. Analyzing climate risks for all value chain stages is helpful because it fosters a more systemic approach to risk management by looking beyond production (39). Climate risk assessment in the rice value chain involves identifying, evaluating and mitigating the impacts of climate-related hazards on various stages of rice production, processing, distribution and consumption (85).

Climate change-driven losses in the value chain will increase as climate extremes become a regular phenomenon with increased frequency and intensity. Some recurring climate changes that tend to cause losses of approximately 3,492-3,823 million Indian rupees (INR) in the rice value chain in the Indo-Gangetic Plain of India include an increase in temperature, a higher number of dry and hot days with a decrease in rainfall, changing patterns of rainfall, an increase in temperature extremities, shifting of seasons, and long spells of high temperature and humidity (86). The UNDP (86) report indicated the storage loss, quality loss and processing loss of 990, 2250 and 250 million INR in the rice value chain due to climate change in the Indo-Gangetic Plain. Floods affect the entire rice value chain, from input supply to consumption activities. Input supply is affected by reduced quality of seeds and delayed deliveries of rice seeds due to flooding. The production component of the rice value chain faces critical challenges due to the occurrence of floods that lead to a reduction in rice yield, destruction of crops, reduced quality of rice crops and consuming more time and labour for weeding, harvesting and drying the produce. Processing functionality is hindered by flood risk, which reduces the volume of rice available for milling, deteriorates the rice quality, increases the grains' moisture content, results in more grain breakage at milling and delays deliveries of the produce. Floods disrupt marketing activities by destructing transportation routes, causing product losses due to rotting and increasing transportation costs. Consumers in the rice value chain suffer reduced availability of grain and higher food grain prices due to flood events (87).

Climate change presents quality-related challenges by affecting the quality of produce and causing fluctuations in the desired price of the produce (71). Rain during harvesting and improper drying of grains would affect the colour of the rice and eventually fetch a lower price. The prevalence of unfavourable climatic conditions at the grain filling phase might produce weaker grains with higher brittleness, affecting rice quality. Adverse climatic conditions inflict quality-related challenges, which consequently emerge as enormous challenges for millers as they are significantly dependent on quality to meet set quality standards (88).

The effects of climate change on rice production have a cascading impact across the whole value chain. Climate risks during rice production affect the seed material supply to the input providers by reducing the quantity and quality of seeds. Production challenges emerge due to climate risk, reducing the rice volume available for milling. Heat stress-induced poor grain quality raises breakage rates, decreases processing efficiency and requires additional investment in machinery for sorting and grading (89). Variable moisture content poses operational issues for processing facilities, necessitating ongoing drying and milling parameters modifications. The disruptions in production have an impact on marketing channels, as fluctuations in supply cause price volatility and variations in quality impact market grades and values. Transportation networks need more flexibility to manage erratic harvest volumes, while storage facilities must adjust to shifting humidity patterns. At the consumption end, consumers suffer reduced availability of rice and higher rice prices due to lower production. Changes in quality affect nutritional content and customer acceptance, while price volatility directly impacts food security, especially for disadvantaged communities.

Climate resilience in the rice value chain requires an integrated approach that recognizes and addresses these interconnected vulnerabilities from farm to consumer. Tinsley (90) posits that the rice value chain (RVC) can be broadly categorized into three segments: production, which includes farmers and support services; processing, which provides for parboiling, milling and marketing (Fig. 5). It encompasses rice's ultimate users as well. Because of their interdependence and cascading effect on the entire rice chain, extreme weather and climate variability are potential risk factors among rice value chain actors or RVCAs. The response of the rice value chain may be influenced by climatic variability. They reported that rice marketers were minimally exposed to harsh weather, while rice producers were extremely sensitive. Sensitivity analysis shows that the producers and processors were highly exposed to extreme weather events. Based on the results of adaptive capability analysis, marketers and processors were particularly affected by climate risk (91).

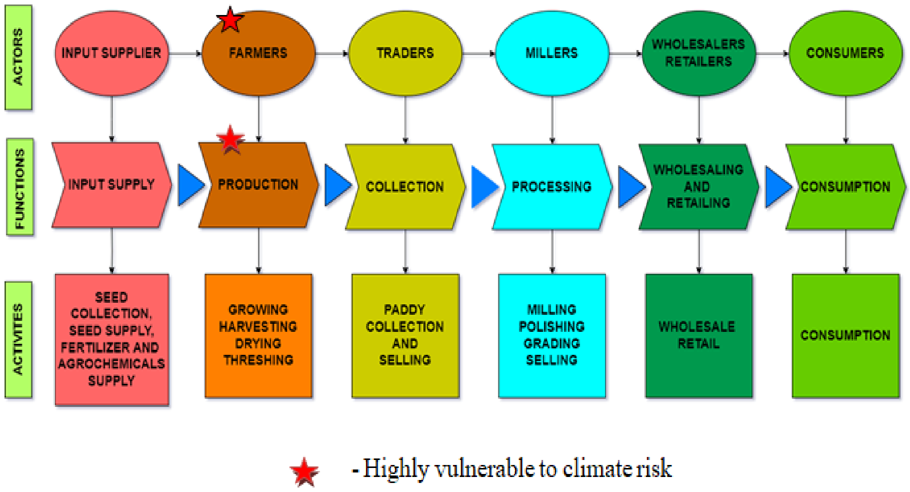

Fig. 5. Conceptual diagram of the Rice Value Chain Actors, functions and their activities

Rice millers mentioned that reductions in moisture during rice processing and non-compliance with quality standards during procurement triggered by climate change account for 4-5% of rice losses in storage, while earlier, this percentage was between 2 and 3% (75). It is difficult for the buyers to return the produce because they have consistent suppliers with whom they have built long-term relationships. Storage insects and pests benefit from higher temperatures and humidity levels because they can increase more quickly in these circumstances, which causes an additional effect of increased fumigation expenses. Grain stored in gunny bags must be periodically fumigated to preserve quality. Under such conditions, warehouses require more fumigation cycles, which raises the cost of warehouse maintenance, as reported by the United Nations Development Programme (UNDP) in India. Extended hot spells are thought to be a significant indicator of climate change. Millers noted that during the ripening stage, high temperatures have the following effects on the paddy crop: Grain weight decreased, grain filling decreased and the proportion of white, chalky, milky rice increased.

Frequent temperature rises and extended drought-like conditions during the rainy season impact the paddy's moisture content, which raises the proportion of broken rice. According to Millers, there has been a 2-3% rise in the proportion of broken rice in recent years (86). According to processors, changes in the climate have led to increased frequency of high moisture, a higher percentage of broken and black rice and a more significant percentage of impurities in the rice recently. These factors impact the cost and quality of rice processing. According to the UNDP (86), this results in a 2-3% loss of the final product and a 90-100 INR loss per quintal of puffed rice produced. The Cambodian rice supply chain risk was investigated using a structural equation model (SEM) and descriptive statistical analysis (92). They discovered that the farm could be exposed to eighteen risk factors, divided into four categories: supply, production, demand and environment risks and proposed risk management strategies and revealed that it should include ex -ante and ex-post risk management strategies.

As per an analysis of the vulnerability of rice value chains in Sub-Saharan Africa, the main points of disagreement over the expansion of the rice industry are the debate over the efficiency and capacity of value chains and the conflict between protectionism and liberalization (92). These discussions, which centre on RVCs' susceptibility to economic disruptions and their ability to adjust to protectionism and liberalization, are related to the research on the vulnerability of RVCs. A framework of crucial tasks for climate risk management (CRM) along agricultural value chains is proposed in their report Enabling Climate Risk Management Along Agricultural Value Chains: Insights from the Rice Value Chain in Uganda (93). It also emphasizes the role of service providers in bolstering CRM initiatives. According to them, development organizations must actively include climate resilience in value chain interventions to fully realize the promise of agricultural value chain development for reducing poverty and ensuring food security.

Adaptation and mitigation of climate risks in rice production and value chain

The estimation of losses resulting from several natural disasters revealed that drought was the leading source of losses, followed by floods and cyclones (94). The three main adaptation strategies can improve rice production, including cultivating drought-tolerant rice varieties, increasing groundwater usage and planting other crops (e.g., wheat, maize, potato and pulses). To bring stability to production, short-term, medium-term and long-term policy measures should be framed (96). Improved water management practices are crucial for managing climate risks in rice cultivation, particularly in changing precipitation patterns, increased frequency of droughts and water scarcity. Adopting water-saving techniques and proper organic manure management in rice contributes to improving soil health, increasing paddy productivity, reducing fertilizer application costs, sequestering carbon, lowering greenhouse gas emissions and helping achieve sustainable development goals (49). In many rice-growing regions worldwide, alternate wetting and drying (AWD) is a well-liked water conservation method. Compared to flooded conditions, AWD saves 13 to 16% of water (97). Drought stress can be mitigated by providing supplemental irrigation at critical crop growth stages. Tube well irrigation has proven cost-effective and timely (64, 98). Irrigation techniques like AWD, micro-irrigation, soil moisture conversation practices and sensor-based automated irrigation would be helpful to farmers in mitigating the impacts of water scarcity.

Developing rice varieties tolerant to various abiotic stresses like drought, submergence and salinity with seed dormancy for at least one month through various breeding programmes can mitigate the ill effects of abiotic stress (99). Swarna Sub1, a flood-tolerant rice variety, is ideal for regions where flash flooding is expected. Drought-resistant rice varieties like CO 51 and ADT 45 have been bred specifically to withstand periods of limited water, making them suitable for Tamil Nadu, India. Short-duration varieties such as ADT 37 and IR 64 are advantageous for Tamil Nadu, allowing farmers to maximize yield with less water while enabling multiple crop cycles yearly. These varieties also reduce the risk of crop loss from delayed monsoon rains. Salt-tolerant varieties like TRY (R) 2 and White Ponni are suitable for coastal regions of Tamil Nadu. Certain adaptation technologies, such as planting at the right time and implementing the rice intensification (SRI) system, could support rice yields in the face of changing climate conditions (100-101). The best type of agricultural diversification in cyclone-prone areas is an annual, perennial crop mix on a farm. Tree crops might sustain less damage than field crops during calamities (102). Land shaping is practiced in Sundarbans, west Bengal, to manage the saline water intrusion (103).

Conservation Agriculture Practices such as zero tillage, mulching and crop rotation can improve soil health, increase water retention and reduce greenhouse gas emissions from rice fields (27, 104). Efficient use of fertilizers and organic amendments, combined with practices such as integrated nutrient management and precision agriculture, can help optimize nutrient uptake by rice plants while minimizing nutrient runoff and environmental pollution. Several rice models will be employed to develop adaptation strategies for risk reduction (101). The most frequently used crop models include ORYZA, the World Food Studies (WOFOST) model, The Agricultural Production System Simulator (APSIM) (24, 105,106), the Crop Environment Resource Synthesis (CERES) model (6) and the Environmental Policy Integrated Climate (EPIC) model (107,108), which provide farmers with access to timely and accurate crop information as well as appropriate management practices to be followed under the forecasted weather, seasonal climate outlook based crop planning and agronomic advice tailored to local conditions (109). This empowers farmers to make informed decisions and adjust their farming practices in response to changing climate patterns. It takes a multifaceted, realistic implementation plan that connects scientific sophistication with local usability to make crop modelling and GIS technology accessible to smallholder farmers. Mobile-based applications can convert complicated modelling data into actionable recommendations in local languages. GIS technology empowers small farmers by providing essential data on soil quality, crop health and weather, helping them make informed decisions about planting and resource use. Affordable GIS apps allow precise application of water and fertilizers, reducing costs and environmental impact.

Additionally, GIS alerts farmers to extreme weather, helping them safeguard their crops and livelihoods. Establishing agricultural knowledge centres and farmer cooperatives can aid in sharing expenses and technical skills at the community level. Implementing early warning systems through well-known channels such as local radio broadcasts, WhatsApp groups and SMS warnings can easily access climate information. Without requiring complex scientific expertise, farmers can make well-informed decisions using essential decision support tools like colour-coded risk maps and smartphone apps that display the best times to plant. Facilitate access to markets and financial services for smallholder rice farmers, particularly during climate-related emergencies or periods of reduced productivity. This can include access to credit, market linkages and support for value-added processing to diversify income sources and build resilience (110).

Among the ways that climate-smart pest and disease management strategies can help lessen the impact of pests and diseases on rice production are biological control methods, resistant cultivars and cultural practices. As a result, fewer chemical pesticides are required and the danger to the environment is decreased (111). Farmers can adapt to changing climatic conditions and make well-informed decisions by receiving tools, education and training on climate-smart agricultural techniques through knowledge sharing and capacity building. Through policy initiatives like subsidies for climate-smart technology, crop insurance schemes, and incentives for sustainable farming practices, governments may be able to significantly contribute to the production of climate-resilient rice and support the research and development of resilient crop varieties (57, 89).

Adapting to and mitigating climate risks is crucial for rice input dealers to ensure the resilience of rice production systems. Depending on the anticipated conditions for the growing season, input providers may need to stock different types of inputs as part of adaptive management (93). Offer a diversified range of rice varieties and input products resilient to various climate risks, such as drought-tolerant seeds, flood -resistant varieties and pest- and disease-resistant inputs. Strengthen the resilience of the input supply chain by diversifying sourcing locations, establishing buffer stocks of inputs and implementing contingency plans for disruptions caused by climate-related events (112). This ensures the continuous availability of inputs, even in the face of supply chain disruptions.

Adaptation and mitigation strategies for climate risks are essential for rice processors to ensure the resilience of their operations and supply chains. By diversifying sourcing locations and establishing buffer stocks of rice and other essential inputs, we can strengthen supply chain resilience. This helps mitigate the impacts of climate-related disruptions, such as extreme weather events or crop failures, on the availability of raw materials. Purchasing paddy in small amounts, storing it, selling it off, purchasing insurance, and diversifying their sources of income are some of the adaptation strategies used by rice processors (113). Enhancing postharvest management by implementing better techniques, such as postharvest mechanization and a supplementary service sector, lowers losses, boosts productivity and profitability and enhances the rice value chain (114). Provide training and capacity-building programs for employees to raise awareness of climate risks and equip them with the skills and knowledge needed to implement climate-resilient practices within processing operations (93). Diversifying product offerings and investing in product innovation to adapt to changing consumer preferences and market demands influenced by climate change (113). This may include developing value-added rice products, fortified rice varieties, or products targeted at niche markets. The vulnerability of rice value change to the effects of climate change will be lessened by policies and programmes that enhance processing facilities storage equipment, encourage the use of weather-based index insurance in rice processing and increase the adaptive capacity of rice processors (113). To maintain the resilience of their supply chains and businesses, rice wholesalers and retailers must implement adaptation and mitigation strategies for climate risk.

Diversifying supply sources entails building relationships with several rice suppliers from various geographic regions to reduce the risk of supply disruptions from climate-related events like extreme weather, droughts, or floods. Diversification makes a consistent rice supply possible even if unfavourable weather strikes one area. Supply to customers is guaranteed when efficient inventory management techniques are used to track stock levels and predict demand swings. Rice stocks can be protected from climate-related hazards and losses can be minimized by investing in climate-resilient infrastructure such as temperature-controlled storage facilities, warehouses with flood protection measures and backup power systems. Implementing a system that intends to initiate and integrate communication with policymakers, industry associations, and stakeholders can help achieve advanced climate-smart business practices and sustainable agriculture (85). Water conservation by consumers relieves pressure on freshwater resources, particularly in drought-prone areas. Through their consumption decisions and actions, rice consumers can also support climate resilience (115).

Research gap

The main conclusions of the literature review are outlined here. The literature focuses on how climatic factors like temperature, rainfall, relative humidity, windspeed and solar radiation affect rice production systems in agriculture. Studies that have been done on the impact on value chains and adaptive measures that are currently available show that these actions and measures are typically taken by actors in isolation and are reactive. They are still too unit-specific and disorganized to be able to reduce risk throughout the whole value chain. The evidence of postharvest adaptations in value chains is less well documented. A few studies describe the rice commodity but fail to highlight how climate change affects various actors in the chain. Since most direct climate risks and vulnerability exposure are more noticeable during the pre-harvest stage, the literature also focuses on mitigation strategies farmers or companies/businesses implement during the production stage. The decline at the production stage indirectly impacts the value chain.

Conclusion

Rice is the primary food grain for half the world's population, which is highly susceptible to adverse weather conditions and needs to be made climate-resilient for rice production. Among the weather parameters, high and cold temperatures play the foremost role in reducing the yield, as they directly and indirectly affect the crop. Excess rain at the time of harvest and drought at all stages drastically affect the rice crop yield. As an indirect effect, relative humidity affects pollen viability more at higher air temperatures. More studies could be done in the future for climate resilience in rice by carrying out various breeding programmes and biotechnology techniques. On reviewing the literatures, advanced studies in the micrometeorology of rice were found to be very few. The old studies should be revised with innovative research and new varieties to unravel crop and climate interactions efficiently.

More work should be done to minimize the challenges in climate risk assessment. The GIS application is beneficial in visualizing the spatial and temporal variations in the vulnerabilities and has been effective in risk mapping. Employing crop simulation models in risk assessment and other methods helps stimulate yield losses under various risk scenarios. The different remote sensing methods should also be utilized to assess climate risk. Climate change affects production and every component in the value chain through direct and indirect means. This review found that a very small number of studies were done regarding climate risk assessment via the value chain approach in rice. In many papers, the actors in the value chain, such as growers and processors, were focused. Still, other actors like input dealers, wholesalers, retailers and consumers weren't included and a research gap was found. Many climate-smart agriculture strategies are available to adapt and mitigate climate risk that builds climate resilience in rice production. More studies could be conducted to emphasize the value chain approach, evolve a smart climate chain and ensure food security for effective climate risk management. Future studies can clarify to what extent and in what forms different development policies hinder or enhance the resilience of rice value chains (RVCs) to multiple exposures. An integrated, interdisciplinary approach that uses the complementing knowledge of agronomy, climatology and economics is necessary to address the complex issues raised by climate change in the rice value chain. Stakeholders can create holistic solutions and exploit synergies to improve global rice systems' sustainability and climate resilience by coordinating research, development and policy activities across various spheres. The rice value chain can be changed through cooperative efforts spanning market assessments, crop enhancement, climate risk assessment and policy interventions to better adapt to a changing climate's effects. This multidisciplinary approach can aid the shift to a more resilient and equitable agricultural system, which can ultimately improve food security and safeguard the livelihoods of millions of rice farmers and consumers.

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Authors' contributions

RA collected the literature and wrote the article under VG's guidance. SM, DM, RR & KB have contributed to improving the manuscript. KB & KS carried out the corrections and improved the manuscript. SMK & MS helped summarize and edit the manuscript. All authors read and approved the final manuscript.

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