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RESEARCH ARTICLE

A systematic literature review on current status and future prospects of pre-harvest sprouting management in rice

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Abstract

Pre-harvest sprouting (PHS) is a major constraint to rice in areas having high rainfall during late maturity. It poses a significant challenge to farmers, leading to yield loss and grain quality. Prolonged wet and humid conditions prevailing in North East India and incidence of cyclonic storms and heavy floods in other states cause PHS in rice. This systematic literature review (SLR) explored existing research on PHS's physiological, biochemical, molecular and environmental factors. A thorough approach that included a methodical Scopus literature search turned up 1236 papers, of which 60 research were selected for quantitative analysis following inclusion criteria. The papers dissected the genetic basis, population studies and genome analysis. Findings of seed dormancy regulation, Quantitative trait loci (QTLs) associated with PHS resistance, genes involved in improving seed dormancy, reducing abscisic acid sensitivity and breeding RILs and NILs resistant to PHS were published. Molecular and biochemical studies reported heat shock proteins (HSPs), hormone-related genes (ABA and GA) and microRNAs as potential targets for developing strategies to prevent PHS in rice. Resilience to pre-harvest sprouting was attempted through exogenous application of chemicals such as eugenol, sodium chloride, glucose, coumarin, molybdenum, maleic hydrazide and uniconazole. Despite current management practices, challenges persist due to the absence of universally resistant varieties and the variability in environmental conditions. Potential gaps identified were a lack of research papers from Indian authors on PHS, a simple and novel technology for the farming community to arrest PHS under unfavourable environmental conditions. Future research directions emphasize integrating laboratory insights into genetic and molecular mechanisms into practical field technologies.

Keywords

dormancy; germination; physiology; pre harvest sprouting; rice; systematic literature review;

Introduction

Rice is the most widely grown crop among cereals (1). Pre-harvest sprouting (PHS) or viviparous germination is a critical issue as it leads to the germination of rice grains on the mother plant itself before harvest, affecting grain quality and causing significant economic losses (2). The onset of PHS is influenced by environmental factors such as humidity, temperature and rainfall during the grain-filling period (3). Due to extended periods of rainy weather, pre-harvest sprouting commonly occurs in rice, which results in significant production loss and a decrease in grain quality (4). The seeds that germinate before harvesting degrades the quality of the food and lowers market value (5). Cyclonic storms that flooded rice fields with excessive rains during the grain maturation period (October-November) significantly negatively impacted rice production. As the plants settle on the ground, pre-harvest grains absorb more rainwater. Rice productivity can be further increased using particular physiological characteristics (6).

In Tamil Nadu, such calamities occur during the harvest of the rabi season rice crop (Oct-Nov) and samba season rice crop (January). Even the lodging-resistant varieties show pre-harvest sprouting when exposed to continuous rain drizzles from the middle soft dough stage to an initial yellow ripe stage of rice seed. Hence, the phenomenon involving the germination of the seeds in the mother plant before harvest is known as pre-harvest sprouting. The high-yielding rice cultivars of Tamil Nadu *viz.,* CO 51, CO 54, CO 55 ADT 53, ADT 56, ADT 57 (short duration); ADT 54, CO 52, TKM 13 (medium duration) and ADT 51, ADT 52, CR 1009 *Sub*1 (long duration) varieties lack dormancy to escape the onset of erratic weather, leading to reduced grain yield and quality causing economic losses to farmers.

Pre-harvest sprouting is a complex process that requires monitoring of physiological, hormonal, and genetic alterations, particularly in rice (2). In rice crops, seed dormancy is essential for determining the crop's resilience to pre-harvest sprouting during climate abnormalities like high temperatures and extended rainfall (7). In rice seeds, dormancy is controlled by the interplay of ABA and GA, each of which is counterproductive to the other. PHS can be avoided by translating the fundamental understanding of hormone biology in seeds to technological advancements. (8). Pre-harvest sprouting (PHS) in cereal crops is caused by ABA deficit during the seed maturation phase, which requires molybdenum cofactor (MoCo) for ABA biosynthesis (9). Similarly, NaCl prevents rice seeds from germinating by lowering bioactive gibberellins (GAs), like GA_1 and GA_4 (10). Chlorates are oxidizing substances considered phytotoxic to all green plant parts (11).

To address this issue, a systematic literature review was undertaken to explore the existing research on managing pre-harvest sprouting in rice crops. The significant challenges are the absence of universally resistant varieties, the genetic traits influencing PHS and the variability in environmental conditions. To address these challenges, a comprehensive approach is required. We aim to find the best management strategies to control pre-harvest sprouting. Therefore, we perform a systematic review of preharvest sprouting management studies using a rigorous search strategy focussing on the breeding techniques, biochemical, genetic and molecular markers, hormonal balance, chemical treatments and climate-smart agricultural practices to develop rice varieties or technologies or chemical formulations to manage pre-harvest sprouting and secure resilience in rice production systems.

Materials and Methods

Information sources and search strategy

A systematic literature search was performed using the Scopus database https://www-scopus-com.elibrarytnau.remotexs.in/, making a comprehensive overview of available literature. Various combinations of keywords related to preharvest sprouting were considered when searching the research papers. A total of 13 keyword combinations, as given in Table 1, were used to search in the database.

Inclusion and exclusion criteria

Inclusion and exclusion criteria were used for the initial screening of the articles to select relevant publications from the search results obtained from the Scopus database. Using the automation filters provided by the databases, non-English, restricted access, review papers, and book chapters were deleted from the records. Publications from the specified subject areas, such as Agricultural and Biological Sciences, Biochemistry, Genetics and Molecular Biology, Environmental Science, Chemistry, Multidisciplinary, Immunology and Microbiology were included, using inclusion criteria.

Relevancy, Duplicates and quality assessment

The PRISMA flow diagram was used to depict the number of studies finally taken for systematic literature review (12, 13). Initially, the Scopus database uses the identification phase and provides pre-harvest sprouting publications. Secondly, the screening phase removed the non-relevant contents, duplicates and selected articles based on original studies reporting physiological, biochemical, and molecular mechanisms underlying pre-harvest sprouting

Table 1. Keywords used as search strings in the Scopus database

S. No.	Search Strings
1	"Pre-harvest" and "Sprouting" and "Rice"
2	"Pre-harvest" and "Sprouting" and "Dormancy"
3	"Pre-harvest" and "Sprouting" and "Germination"
4	"Pre-harvest" and "Sprouting" and "Inhibition"
5	"Pre-harvest" and "Sprouting" and "Physiology"
6	"Pre-harvest" and "Sprouting" and "Genetics"
7	"Pre-harvest" and "Sprouting" and "Gene expression regulation"
8	"Pre-harvest" and "Sprouting" and "Phytohormones"
9	"Pre-harvest", and "Sprouting" and "Gibberellin"
10	"Pre-harvest" and "Sprouting" and "Abscisic acid"
11	"Pre-harvest" and "Sprouting" and "PHS resistance"
12	"Pre-harvest" and "Sprouting" and "Crop yield"
13	"Pre-harvest" and "Sprouting" and "Grain quality"

and field and chemical management of pre-harvest sprouting. Full-text articles were further screened based on relevant titles and abstracts involving automated filters. Finally, the eligibility assessment phase included all original studies aiming to control pre-harvest sprouting in rice through appropriate management strategies.

Bibliometric analysis

All the eligible articles were analysed using R-Studio to identify author and co-author networks, depicted through a VOS viewer. Countries' citation networks regarding pre-harvest sprouting in rice were then analysed. Author co-author networks were also retrieved from the VOS viewer. Thematic mapping highlighting the need for a comprehensive strategy for future research projects on rice pre-harvest sprouting management was obtained through R-Studio by uploading all sixty full articles.

Results

Publication analysis from search strings

The database search using 13 keyword combination searches resulted in 1236 articles. The search strings were designed to encompass different aspects of pre-harvest sprouting. The search string focused mainly on pre-harvest sprouting in rice, resulting in 98 publications. The graph provided similar information for various combinations of keywords such as dormancy, germination, inhibition, physiology, genetics, gene expression regulation, phytohormones, gibberellin, abscisic acid, PHS resistance, crop yield and grain quality (Fig. 1).

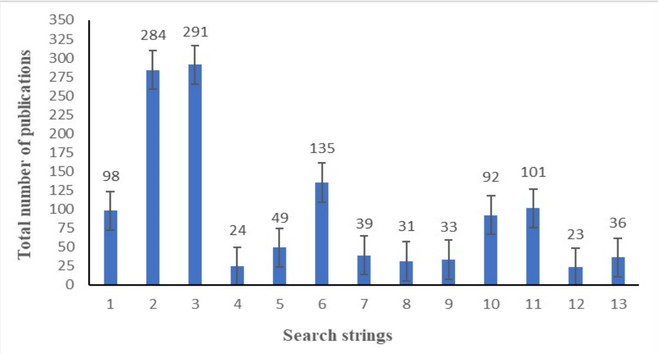

Fig. 1. Search strings used and the total number of publications from the Scopus database

This systematic literature review provided an overview of the current literature on managing pre-harvest sprouting in rice. A total of 1236 studies were found in the Scopus database (Fig. 2). these studies were screened using inclusion and exclusion criteria. The most frequent reason for the exclusion of a study was the research of subjects other than pre-harvest sprouting, followed by review papers and non-English papers; using this criterion, 669 articles were removed. The remaining 567 articles underwent further screening based on the title and abstract. After the screening, 496 articles were eliminated for the non-existence of predefined keywords in the title, abstract or keywords part of the paper and the publications related to pre-harvest sprouting in the rice crop were included alone. Based on the eligibility criteria, publications focusing on pre-harvest sprouting

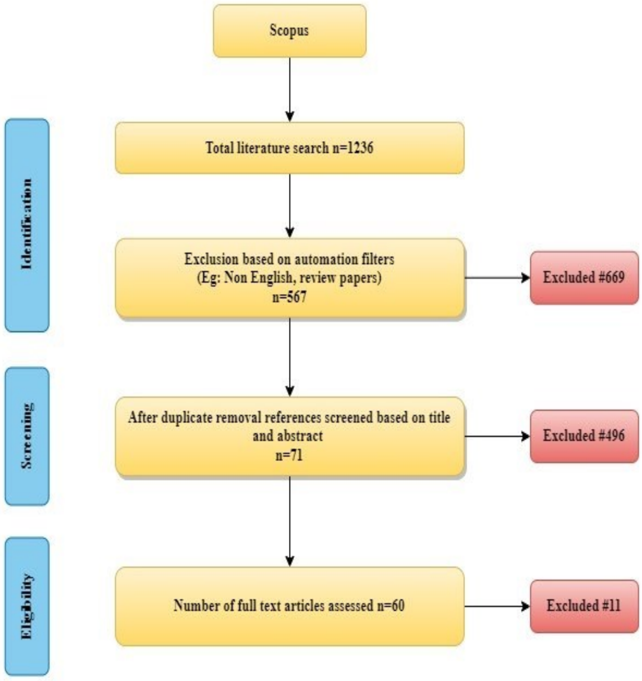

Fig. 2. The PRISMA Flow diagram depicting the number of studies taken for systematic review

management as the primary determinant were also included. A thorough screening of the full-text articles eliminated 11 research studies from 71 research papers. Finally, 60 research findings were chosen for quantitative analysis, which had relevance and clarity in addressing pre -harvest sprouting management in rice. Results revealed that pre-harvest sprouting was a part of many studies and was not the main criterion in most papers. Relevant publications were further refined and filtered using inclusion and exclusion criteria to meet appropriate literature evaluation. (3, 7, 9, 14-69).

Genetic and molecular basis of pre-harvest sprouting management

The full-text articles included research on the genetic approach to study the seed dormancy regulation, quantitative trait loci (QTLs) associated with PHS resistance and gene characterization to examine the ABA sensitivity and ABA signalling to control pre-harvest sprouting in rice. Various seed dormancy regulators *viz*., weak seed dormancy 1 (*WSD1*), ent-kaurene oxidase 1 (*OsKO1*), phytoene desaturase (*OsPDS*), ζ-carotene desaturase (*OsZDS*), carotenoid isomerase (*OsCRTISO*), lycopene β-cyclase (*b-OsLCY*) were identified to regulate the balance of ABA and GA pathways showing increased seed dormancy leading to increased ABA levels and inhibition of pre-harvest sprouting (22, 32, 37, 47, 64). The theory findings demonstrated that an interplay between ABA and GA pathways must delicately balance one another to regulate seed germination. Two QTLs, *qSDR9.1* (Seed dormancy 9.1) and *qSDR9.2* (Seed dormancy 9.2), governing seed dormancy, were identified on chromosome 9 of rice cultivars. When introduced in Ninggeng 4, these QTLs increased pre-harvest sprouting resistance and improved grain quality in rice (48, 50). Similarly, overexpression of *Oryza sativa* MOTHER OF FT (FLOWERING LOCUS T) AND TFL1 2(TERMINAL FLOWER 1)

(*OsMFT2*) and MAPK (mitogen-activated protein kinase) kinase kinase 62 (MKKK62) were found to positively upregulate ABA-responsive genes and negatively regulate the ABA sensitivity providing pre-harvest sprouting management (46, 56). Identified QTLs and overexpression of genes can fine-tune the selection in rice breeding, aiming for pre-harvest sprouting resistance. Thus, the complex mechanisms controlling seed dormancy were understood from the findings of the above authors.

The development of recombinant inbred lines and knockout mutants with QTLs involved in improving seed germination activity in rice was found to be resistant to pre-harvest sprouting (42). Population studies and genome analysis have identified potential genes within 100kb and single nucleotide polymorphisms (SNPs) within specific genes to be linked with seed dormancy (55). Two QTLs, *qPHS-11 GH* (quantitative trait locus for panicle harvest stage 11 grain hardness) and *qPHS-11 FD* (quantitative trait locus for panicle harvest stage 11 grain fertility disorders) were identified on chromosome 11 of japonica rice varieties were found to confer stable PHS resistance (18). The identified QTLs from various population and genome sequencing studies have given leads for practical application in breeding initiatives.

Transcriptomic profiles of RNAase and microRNAs in seed embryos and endosperm identified HSPs and hormone-related genes that could potentially develop pre-harvest sprouting-resistant rice varieties. (44, 51). Protein-protein interactions between *Oryza sativa* DELAY OF GERMINATION 1 (*OsDOR1*), a negative regulator of GA signalling and GA receptor protein *Oryza sativa* GIBBERELLIN-INSENSITIVE DWARF 1 (*OsGID1*) in rice, block the pre-harvest sprouting (38). So, the biochemical investigations reveal the role of higher HSPs and lesser GA as potential targets for developing rice types resistant to pre-harvest sprouting.

Hormone engineering, chemical methods and field management to control pre-harvest sprouting in rice:

Pre-harvest sprouting resistance was associated with diverse physiological and hormonal levels such as ethylene, ABA and GA (70). Hormonal signals play a dominant role in determining whether seeds germinate or not. The two main phytohormones that contradict each other to control seed germination and dormancy are ABA and GA. The dynamic balance between hormone catabolism and biosynthesis controls the amount of ABA in cells. Decreased ABA often accompanies dormancy release due to altered expression patterns of synthetic and catabolic genes (70). The loci and genes have been identified as viable resources for developing pre-harvest sprouting-resistant varieties (19). Rice mutant populations exhibited pre-harvest sprouting phenotype accompanied by sugary endosperm. These mutants showed altered ABA signals regulating seed dormancy and germination (21). Engineering plants to express ABA has been attempted. NCED (Nine-cis-epoxy carotenoid dioxygenase) of ABA biosynthesis was successfully used to suppress the germination of Arabidopsis seeds (8). Hyper dormancy caused by NCED systems can be reversed by counteracting genes, such as NCED RNA interference or Gibberellin biosynthesis genes. Thus, pre-harvest sprouting can be arrested by incorporating the fundamental understanding of hormone biology in seeds into technological applications (Table 2 and 3).

Shedding light on field practices and environmental considerations, the study revealed that simulated flooding led to pre-harvest sprouting in japonica and indica rice varieties (59). Heat treatment and physical methods of inducing seed dormancy also play an essential role in bringing resistance against pre-harvest sprouting in rice. Heat treatment at 45°C eliminated the dormancy by regulating the α-amylase activity and ABA concentration (24). The function of β-amylase in pre-harvest sprouting was also enhanced under high temperature and humidity, as seen in the genetically modified rice (58). The significance of customising crop management strategies to individual rice cultivars is shown by the variations in dormancy between varieties and the effects of simulated flooding. Furthermore, demonstrating the interplay between genetic variables and environmental factors emphasises the necessity of a comprehensive strategy to manage pre-harvest sprouting in rice farming.

Pre-soaking of seeds in different concentrations of eugenol, NaCl, glucose, coumarin and molybdenum were found to inhibit seed germination speed, α-amylase activity and increase the internal abscisic acid (ABA) content in seeds (9, 10, 31, 71, 72) thus, reducing pre-harvest sprouting. Combined as inhibitors, maleic hydrazide, uniconazole, and eugenol dramatically decreased the activity of α-amylase, an enzyme essential for germination (30). Similarly, the inhibitor combinations of Maleic hydrazide, uniconazole and eugenol significantly suppressed rice's pre-harvest sprouting and seed germination speed. These chemical techniques provide practical applications to decrease pre-harvest sprouting damage in areas prone to high temperatures and wet weather. In addition to genetic improvements and molecular tools to prevent pre-harvest sprouting in rice, applying exogenous chemicals is a practical approach to arrest pre-harvest sprouting. Studies suggest that chemical biology can manipulate seed germination by regulating the internal ABA and GA contents, which shows increased resilience to pre-harvest sprouting.

Discussion

This literature study's strength is its systematic and broad search of the Scopus database. It gives a clear overview of the known literature. However, research gaps must be focused on to evolve a management strategy for pre-harvest sprouting in rice. The thematic analysis using R-Studio has explored the various dimensions of research in pre-harvest sprouting. All the papers are segregated into four themes: niche, motor, essential, and emerging declining themes. The research categories, such as plant botany dealing with the regulatory process behind seed dormancy and physio-chemical characteristics of pre-harvest sprouting of rice crops, are classified under basic

Table 2. Genetic, molecular and biochemical basis of PHS in rice

Theme	Mechanism	Result	Reference
Genetic approach			
Seed dormancy regulation	A seed dormancy regulator named *WSD1* in rice was used to study the balance of ABA and GA pathways.	*WSD1* mutant showed a higher seed germination percentage	(32)
	Mutations in the microRNA (miRNA) precursor MIR156 and *OsKO1* suppress rice's enzyme activity and GA pathway.	Mutations in the MIR156 subfamily enhanced seed dormancy and suppressed PHS. *OsKO1* catalyses the reaction from ent-kaurene to ent-kaurenoic acid in GA biosynthesis.	(47)
	Mutations in genes (*OsPDS, OsZDS, OsCRTISO, b -OsLCY* reduced the levels of ABA.	Increased activities of reactive oxygen species (ROS) scavenging, carotenoid biosynthesis pathway led to pre-harvest sprouting and photo-oxidation in rice	(22)
QTL Analysis	Two QTLs, *qSDR9.1 and qSDR9.2*, on chromosome 9, with the 'Owarihatamochi' alleles reducing germination and increased PHS resistance in rice	Owarihatamochis' allele on chromosome 9 increased seed dormancy and enhanced PHS resistance, grain yield and quality by developing new rice cultivars.	(48)
	Two QTLs, qHTSF1.1 and qHTSF4.1, controlling spikelet fertility under high-temperature stress, were introgressed from Nagina 22 into improved White Ponni (IWP) through marker-assisted breeding.	Two QTLs, qHTSF1.1 and qHTSF4.1 on chromosomes 1 and 4, improved membrane integrity and spikelet fertility in rice	(73)
Gene characterization	Overexpression of *OsMFT2* interacted with three basic leucine zipper (bZIP) transcription factors (*OsbZIP23, OsbZIP66, and OsbZIP72*) and enhanced their binding to the promoter of the ABA-responsive gene *Rab16A,* which delayed germination.	*OsMFT2* positively regulates ABA-responsive genes in rice, leading to the arrest of Pre-harvest sprouting.	(56)
	Overexpression of Pre-harvest sprouting mutant (*PHS9*) and *Oryza sativa* "GTPase-activating protein" (*OsGAP*) resulted in reduced ABA sensitivity, integrates ROS signalling and ABA signalling to control PHS in rice	*PHS9* and *OsGAP* showed reduced ABA sensitivity	(62)
	Overexpression of *MKKK62* negatively regulates the ABA sensitivity and *OsMFT* transcription.	*MKKK62-MKK3-MAPK7/14* modules were found to control seed dormancy in rice by regulating the expression of *OsMFT*	(46)
Marker-Assisted techniques	Near-isogenic lines (NILs) with the Seed dormancy 9 (*qSdr9*) allele from weedy rice "Ludao" in the Ninggeng 4 background were found to decrease germination	qSdr9 locus was identified as a novel QTL for seed dormancy and PHS resistance in weedy rice "Ludao."	(49)
	Genotyping and phenotyping of BC 3 F 3 generation resulted in elite NILs of CO 43 harbouring Sub1 locus.	The marker-assisted backcross breeding (MABB) approach introduced the Sub1 QTLs into CO 43 for submergence tolerance.	(74)
Recombinant lines and knockout mutants	Recombinant inbred lines (RILs) are used to identify genetic characteristics related to seed germination activity in rice, which are resistant to PHS	germination activity (*qGR-7*), seed weight (*qSW7-1*), *qSW7-2*, coleoptile length (*qCL7-1*), and radicle length (*qRL3-1*) that played an essential role in the metabolism of seed.	(42)
Population studies and Genome Analysis			
Population and GWAS	Analysing the expression of candidate genes within 100 kb and SNPs in specific genes associated with seed dormancy	Eight QTLs were found to be associated with seed dormancy in rice	(55)
Genome Analysis	Two QTLs, *qPHS-11 GH* and *qPHS-11 FD* on chromosome 11confer the stable PHS resistance analysed through genome re-sequencing	QTLs identified in this study improved the PHS resistance of japonica rice varieties.	(18)
Molecular and Biochemical studies			
Transcriptomics	Transcriptome and small RNAome analyses in seed embryo and endosperm identified hormone-related genes, heat shock protein-related genes and microRNAs. These could potentially be targeted for developing strategies to prevent PHS in rice.	Heat shock protein genes were associated with the higher PHS rate in rice.	(44, 51)
Protein interactions	The interaction between *OsDOR1*, an opposing player of GA signalling and the GA receptor protein, *OsGID1*, in rice	Over-expression of *OsDOR1* enhanced seed dormancy by suppressing GA activity in rice seeds.	(38)

Table 3. Hormonal engineering and chemical treatment in the prevention of PHS

Theme	Mechanism	Result	Reference
Hormonal regulation			
Hormonal balance	A study of ABA and GA pathways in rice revealed the molecular mechanisms of downstream transcriptional regulation of GA-responsive genes.	Involvement of ethylene, ABA and GA in regulating seed germination in rice	(70)
	OsbZIP09 directly enhanced the expression of the ABA catabolism gene abscisic acid 8'-hydroxylase 1 (*ABA8ox1*), reducing ABA accumulation and promoting seed germination.	*OsbZIP09* mutants exhibited longer seeds and less severe pre-harvest sprouting.	(19)
	A Mutant called pre-harvest sprouting 8 (*phs8*) exhibited a preharvest sprouting (PHS) phenotype accompanied by a sugary endosperm, affecting ABA signalling.	Increased sugar contents in the phs8 mutant led to decreased expression of *Oryza sativa* ABA INSENSITIVE 3, 5 (*OsABI3, OsABI5*) and reduced sensitivity to ABA in rice.	(21)
	Biosynthesis of abscisic acid (ABA) by enhancing the expression of an ABA biosynthesis gene NCED	Switching on NCED alone is sufficient to switch off germination and maintain seed dormancy	(8)
	Anaerobic germination tolerant genotypes had lower levels of seed IAA and higher levels of GA and α-amylase activity.	Higher GA content and α-amylase activities in rice seeds enhance germination under direct-seeded rice cultivation.	(75)
Field management and Environmental factors			
Field practices	The effect of simulated flooding on Indica and Japonica rice cultivars showed greater pre-harvest sprouting.	The greater dormancy of indica rice enhanced resilience to pre-harvest sprouting in rice	(59)
Environmental factors	High temperature and humidity, along with increased GA1 and amylase activity, contributed to pre-harvest sprouting in female parent Gumei-2 (GM-2)	The female parent GM-2 was more prone to pre-harvest sprouting than the male parent Zhong-156 (ZH-1560) due to higher seed GA content.	(58)
Heat treatment and Physical methods	The association between seed dormancy and pericarp colour was controlled by a pleiotropic gene that regulates abscisic acid and flavonoid synthesis at 45°C for one week.	Heat treatment at 45°C almost completely removed dormancy in rice seeds	(24)
Chemical methods			
Inhibitory treatments	Seeds were pre-soaked in different concentrations of eugenol, NaCl, Glucose, Coumarin, and Molybdenum. These chemicals inhibit α-amylase activity and increase the internal ABA content in seeds.	Strongly delayed seed germination and preharvest sprouting in rice	(9, 10, 31, 71, 72)
	Combinations of maleic hydrazide, eugenol, and uniconazole inhibit the activity of α -amylase.	The selected combinations of inhibitors strongly inhibited seed germination speed and preharvest sprouting in rice and had no adverse effects on seed quality.	(30)

themes and the genetics and phylogeny involving genes, QTLs and SNPs underlying pre-harvest sprouting resistance in rice under motor themes explored effectively. The niche themes dealing with phylogeny and SNPs have many publications and have been researched by many authors. However, the emerging themes such as research on chromosomes, alleles and cross-breeding are yet to be explored (Fig. 3). Similarly, chemical manipulations using the external application of chemicals and growth regulators to arrest pre-harvest sprouting at field conditions and molecular breeding to evolve pre-harvest sprouting resistant rice genotypes are some of the critical areas for future research. This should combine the knowledge of molecular, biochemical, environmental and agronomic factors in an integrated manner. Most studies focus on controlled experiments, but translating these findings into practical, field-level solutions is essential. Research that integrates laboratory insights with on-field trials and adoption studies can offer a more holistic understanding of the effectiveness and feasibility of PHS interventions.

The literature survey also depicted the author and co-author network in the research on the management of pre-harvest sprouting in rice (Fig. 4). The network suggested a prolific contribution by the authors majorly from China and South Korea and notable contributions from authors of Japan, US, UK, Australia, Philippines and Egypt (Fig. 5). The figure highlighted a relative lack of studies from India in this research area. This gap in research visibility could be caused by several variables, such as fewer research projects addressing pre-harvest sprouting, low priority assigned to this particular topic, funding limitations and lack of international collaboration. Hence, there is a need to bridge this gap. Researchers and institutions should actively work together, encouraging cross-disciplinary collaborations to manage the pre-harvest sprouting in rice to get better yields and quality.

Conclusion

This systematic literature review critically examined the issue of pre-harvest sprouting (PHS) in rice crops. PHS is known to be significantly influenced by several environmental variables, including temperature, humidity and rainfall during the grain-filling season. The study employed a rigorous screening of research articles, filtered according to inclusion and exclusion criteria. For quantitative analysis, sixty studies were chosen based on clarity, applicability and suitability for PHS management in rice. Genetic and molecular research on this topic has identified negative regulators for ABA sensitivity, QTLs, and genes governing pre-harvest sprouting resistance,

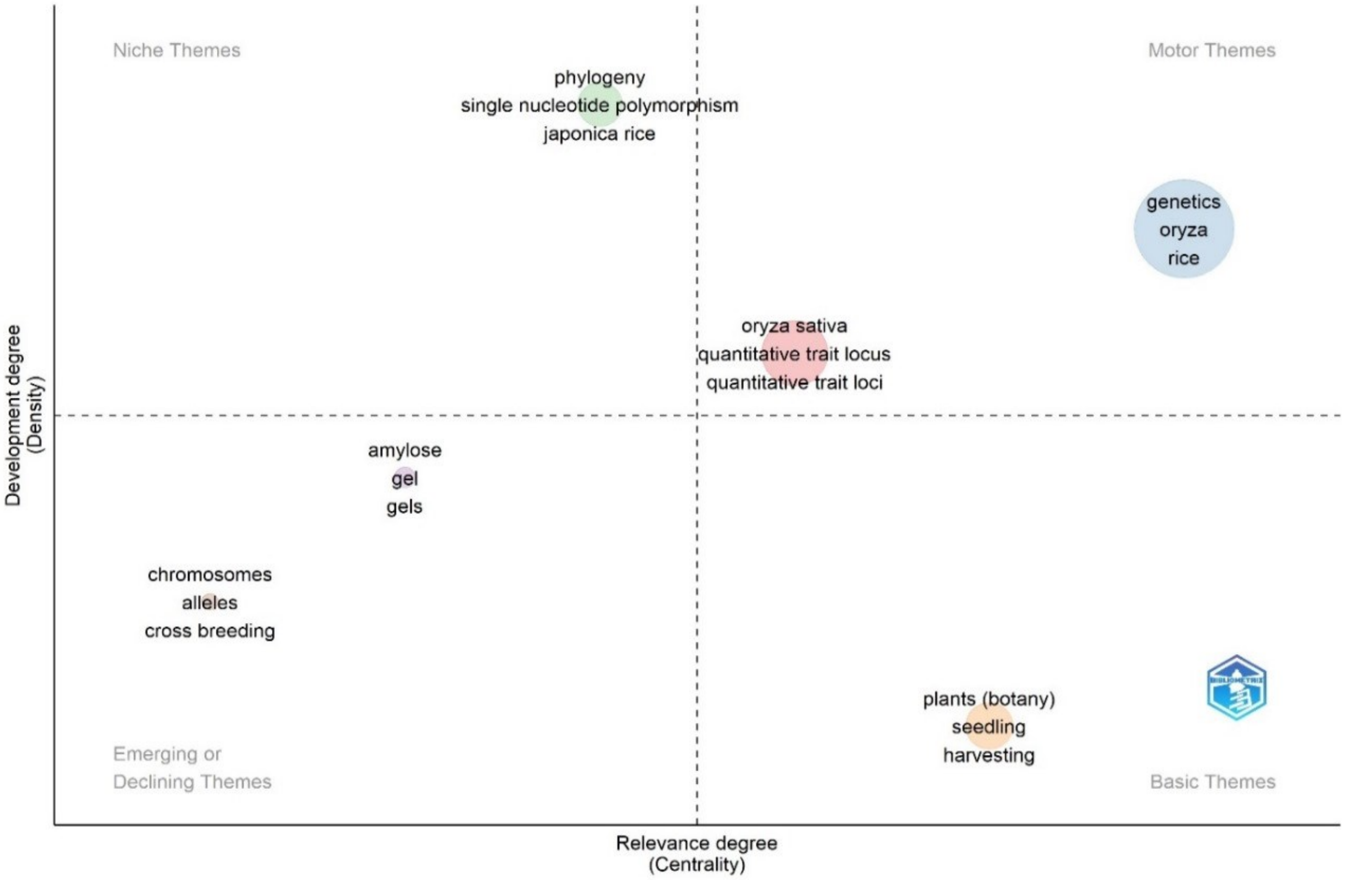

Fig. 3. Thematic analysis of research topics in PHS management of rice

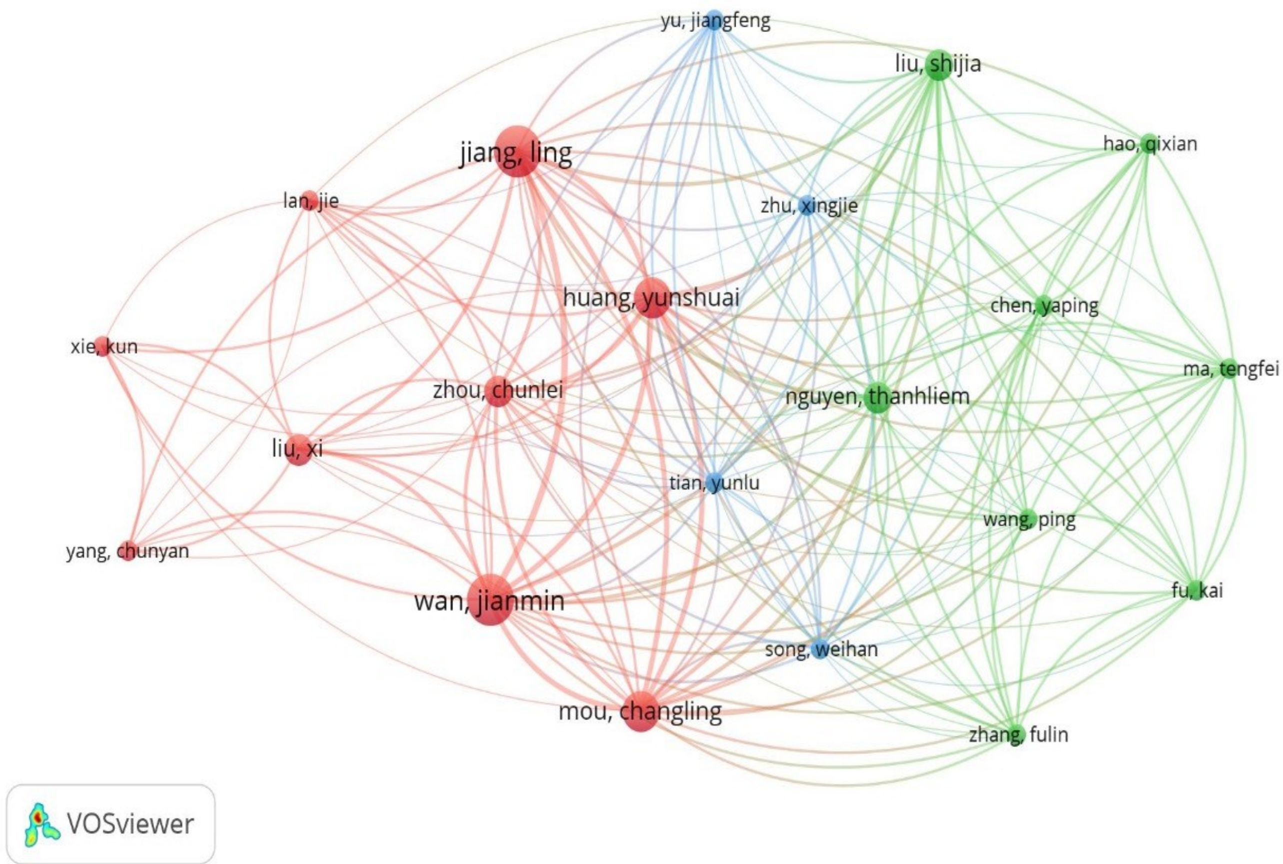

Fig. 4. Author, co-author networks in research papers dealing with PHS in rice

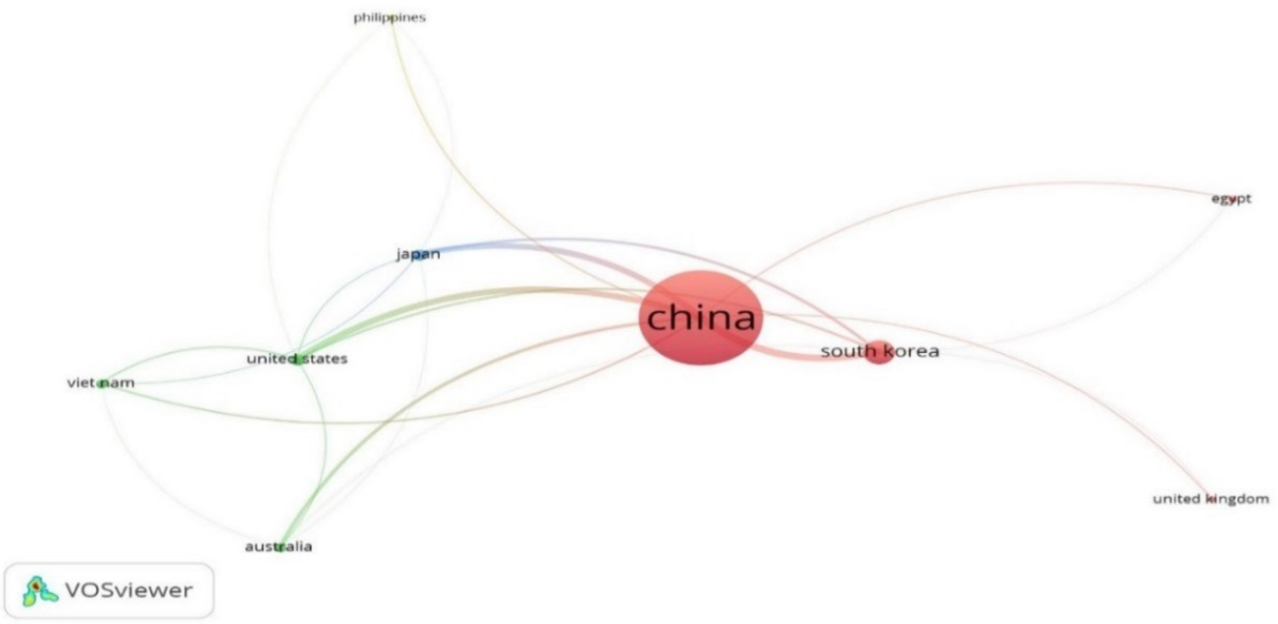

Fig. 5. Mapping the countries and citations on PHS

validated in mutant lines.

Further research on this topic should focus on introgressing the identified QTLs, genes, and novel alleles from various population studies in breeding initiatives to develop rice crops resilient to pre-harvest sprouting. Hormone engineering and chemical biology should be considered when synthesizing technologies or chemical formulations that can arrest the germination of seeds on the maternal plant. A thorough dissection of physiological mechanisms and mode of action of chemical formulations in the control of pre-harvest sprouting will provide a conclusive answer by managing pre-harvest sprouting in rice. International cooperation, economic analyses and outreach programmes are crucial for filling the gaps and advancing PHS research for functional rice crop management solutions. This systematic analysis offers scholars insightful information that lays the groundwork for future research and the creation of comprehensive plans to lessen the effects of PHS on rice production.

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Authors' contributions

All the authors contributed equally to conceptualising the work, interpretation, analysis, writing, reviewing and editing of the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The authors declare that they have no conflict of interest

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

While preparing this work, the authors used Rytr (blog/ content writing AI software) to reframe some sentences to have proper research terms in some parts alone. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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