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Perennial rice – An alternative to the 'one-sow, one-harvest' rice production: Benefits, challenges, and future prospects

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ABSTRACT

The traditional 'one-sow, one-harvest' rice cultivation method faces significant challenges, including high water and energy consumption, soil health degradation, greenhouse gas emissions, increased labor demands, and excessive pesticide use. Perennial rice, a novel no-tillage-based rice system, presents a promising solution with the potential to address many of these challenges. It offers several advantages, such as reduced production costs and labor demands by eliminating the need for repeated land preparation, nursery raising, and transplanting while also lowering environmental impact through energy conservation, soil carbon sequestration, reduced soil erosion, and decreased greenhouse gas emissions. The perennial rice system is gaining traction in China, with the area under cultivation steadily increasing since its release in 2018. Farmers are interested in adopting this system due to its lower labor demand, reduced production costs, and yields and grain quality comparable to local varieties. However, perennial rice brings its own challenges, including yield instability, inconsistency in grain quality, higher irrigation demands, increased risks of pests and diseases, soil sickness, and the lack of suitable agronomic practices, such as optimum crop geometry, weed management, nutrient application, and harvesting techniques. Additionally, it limits crop diversification, making it less suitable for regions with diversified or multiple cropping systems. Despite these limitations, perennial rice demonstrates significant potential in several rice-growing regions worldwide. To fully unlock this potential, focused efforts are needed to develop high-yielding perennial varieties with better grain quality and resistance to pests and diseases. Additionally, region-specific agronomic practices, including optimal crop geometry, effective weed control, innovative nutrient management, and improved irrigation, must be established to optimize this cropping system.

1. Introduction

Rice (*Oryza sativa* L.) is a cornerstone of global food security, serving as a dietary staple for over half of the world's population (Fukagawa et al., 2019). It provides essential carbohydrates, proteins, vitamins, and minerals, making it a fundamental component of diets in many regions (Sen et al., 2020). Beyond its nutritional significance, rice cultivation supports the livelihoods of countless farmers, particularly in Asia, where it is the primary source of income and employment (Muthayya et al., 2014). Additionally, rice holds cultural and symbolic value in many societies, featuring prominently in traditional ceremonies, rituals, and cuisines. Given this multifaceted importance, ensuring the sustainability and resilience of rice production is paramount to maintaining global food security and economic stability (Li et al., 2023). However, rising demand driven by population growth and challenges like resource scarcity, climate change, and environmental degradation underscores the urgent need to reconceive one-sow, one-harvest rice cultivation practices.

1.1. Major sustainability issues of one-sow, one-harvest rice

Paddy cultivation requires far more water than any other crop, leading to groundwater withdrawal for irrigation, depletion of

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groundwater reserve, and increased alkalinity (Subramanian et al., 2023; Ramesh et al., 2024). The resulting strain on water resources is particularly evident in Asia's major rice-growing regions, where per capita freshwater availability is steadily declining (Mallareddy et al., 2023). Irrigation requirements varied considerably according to rice cultivation methods. Puddled transplanted rice exhibited the highest water demand (957 mm), while direct-seeded rice methods demonstrated the lowest (630 mm) (Padma et al., 2023). Rice cultivation is responsible for 10.1% of all greenhouse gas (GHG) emissions from agriculture (Wang et al., 2023). The global GHG emissions from rice systems have a GWP four times higher (657 kg CO_2 eq Mg^{-1}) than wheat (166 kg CO_2 eq Mg^{-1}) and maize (185 kg CO_2 eq Mg^{-1}) (Linquist et al., 2012). The carbon footprint of rice cultivation in India is significantly higher than that of wheat, with rice exhibiting a 92% greater carbon footprint. Similarly, rice production in India demands substantially more water compared to wheat, with a 121% higher water footprint (Nayak et al., 2023).

The indiscriminate and excessive use of nitrogen (N) fertilizers in rice cultivation has resulted in low N use efficiency (25–35%), increased N_2O emissions, and significant environmental pollution (Subramanian et al., 2020; Mboyerwa et al., 2022). In rice growing areas, groundwater contamination from nitrate leaching is particularly severe in coarse-textured soils, where excessive irrigation and overuse of N fertilizer (often 25% more than for loam soils) (Bhatt et al., 2016). Additionally, the mining of potassium (~100 kg ha^{-1} $year^{-1}$) in rice-based systems across South Asia poses a severe threat to sustainability and food security in the region (Vijayakumar et al., 2024). The challenges are further exacerbated by the rising incidence of pests and diseases in rice cultivation, which has grown from just three in 1965 to over 20 by 2018 (Jena et al., 2018). Many minor pests have evolved into major threats over time (Fig. 1). The major reasons for this insect pests shift are highlighted in Fig. 2. Changing climatic conditions, such as rising temperatures, have facilitated the emergence of new pest races and allowed more pests to survive through winter (Skendžić, 2021; Vijayakumar et al., 2023).

Puddled transplanted rice systems also degrade soil structure, leading to the formation of a hardpan, particularly in heavy-textured soils. This hardpan impedes deep percolation and groundwater recharge, while also restricting the root growth of subsequent crops in the system (Bhatt et al., 2016). As a result, these crops struggle to access deep-soil water and nutrients, leading to reduced yields. Moreover, puddled transplanted rice is labor, energy, and cost-intensive (Zhang et al., 2023) and faces challenges such as weed flora shifts, the development of weed resistance, labor shortages, and rising wages. In contrast, direct-seeded rice systems offer significant advantages, including reduced labor requirements and lower production costs, making them a more attractive alternative for conventional puddled transplanted rice cultivation (Pooja et al., 2021). However, this method again suffers from nutrient deficiency like iron and heavy weed infestation, subsequently significant yield loss.

These challenges raise concerns about the sustainability of 'one-sow, one-harvest' rice farming. Therefore, it is crucial to cultivate rice in an alternative way that addresses these threats while preserving ecosystem services and ensuring long-term food security. One promising approach gaining traction in China is perennial rice (PR). This article evaluates the advantages of PR over puddled transplanted rice, identifies challenges within the system, and offers potential solutions to enhance its viability and encourage large-scale adoption, drawing on recent evidence. It also highlights critical research gaps and emphasizes increased investment in PR research, particularly in major rice-producing countries like Bangladesh, Cambodia, India, Vietnam, Thailand, and the Philippines.

2. Perennial rice: a solution to many problems of one-sow, one-harvest rice cultivation

PR varieties offer a sustainable alternative to the traditional 'one-sow, one-harvest' method. These varieties can be harvested multiple times in a year eliminating the need for annual replanting (Zhang et al., 2017; Huang et al., 2018; Yao et al., 2022). PR offers significant cost savings (up to 50% from the second season), reduced chemical pesticide usage, lower irrigation needs, and decreased labor inputs compared to transplanted rice (Huang et al., 2018; Zhang et al., 2023). It also holds the potential to mitigate the environmental impacts of rice farming by sequestering carbon, conserving water, and reducing energy inputs (Gomez and Rodríguez, 2022; Hu et al., 2022). PR is suited to a broad range of frost-free environments between 40° N and 40° S (Zhang et al., 2023). It is currently being tested in 17 countries across Asia and Africa, particularly in upland regions and terraced fields where conventional rice

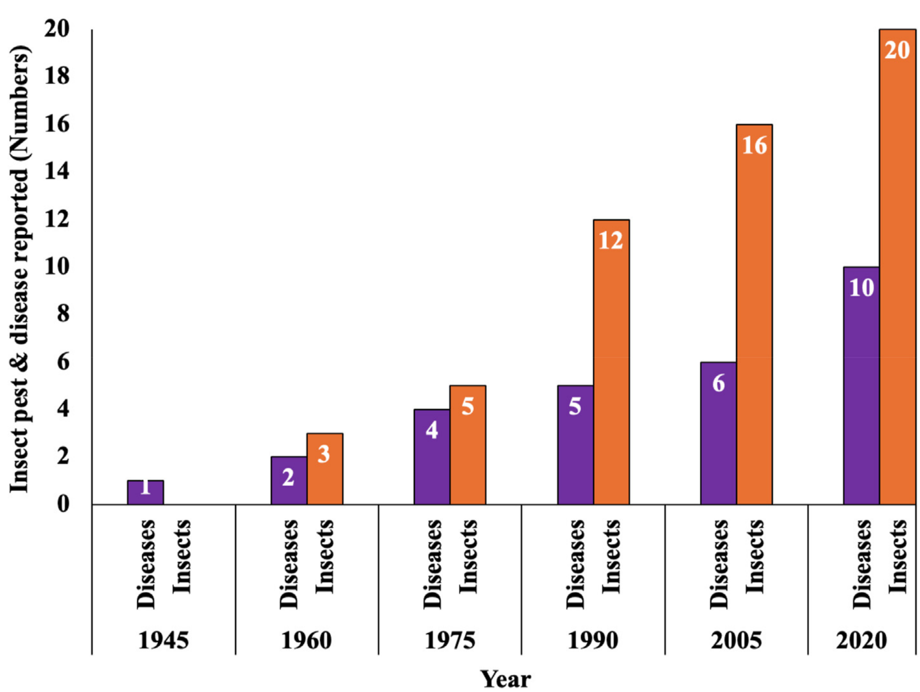


Fig. 1. Trends in insect pests and diseases affecting rice in India (1945–2020).

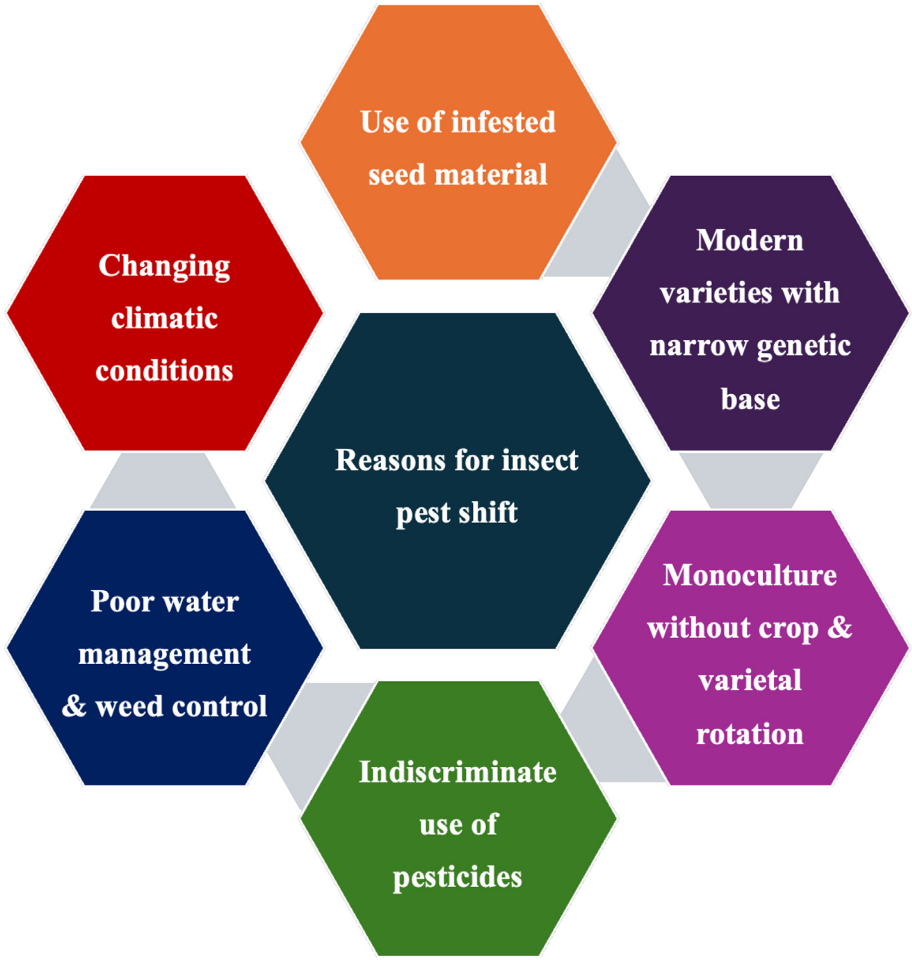


Fig. 2. Factors contributing to the shift in insect pests and diseases in rice cultivation.

cultivation contributes to soil erosion through plowing (Stokstad, 2022).

Perennial Rice-23 (PR23) was the first commercial PR variety developed using the embryo rescue technique and was released in Southern China and Laos in 2018 (Samson et al., 2018; Zhang et al., 2019). The cultivar PR23 was developed with desirable traits such as pollen fertility, rhizomatous propagules, plant height, tiller number, grain number per plant, seed-setting rate, panicle length, grain size, and grain quality similar to elite cultivars of indica ssp. Other perennial rice cultivars, such as PR24, PR25 (Yunda25), PR101, and PR107 (Yunda107), known for their high yield and good grain quality, were released in China in 2020. In 2021, PR107 was also released in Uganda under the name NARORICE-1. It is resistant to rice yellow mottle virus, acquired from its parent *O. longistaminata* (Zhang et al., 2023). PR was grown by 44,752 smallholder farmers in Southern China across 15,333 ha and demonstrated a huge benefit in terms of economy and environment (Zhang et al., 2021). The International Perennial Rice Collaboration, organized by Yunnan University, is currently promoting the adoption of PR in China, Myanmar, Laos, Cambodia, Thailand, Vietnam, Indonesia, Uganda, and Côte d'Ivoire (Hu et al., 2022).

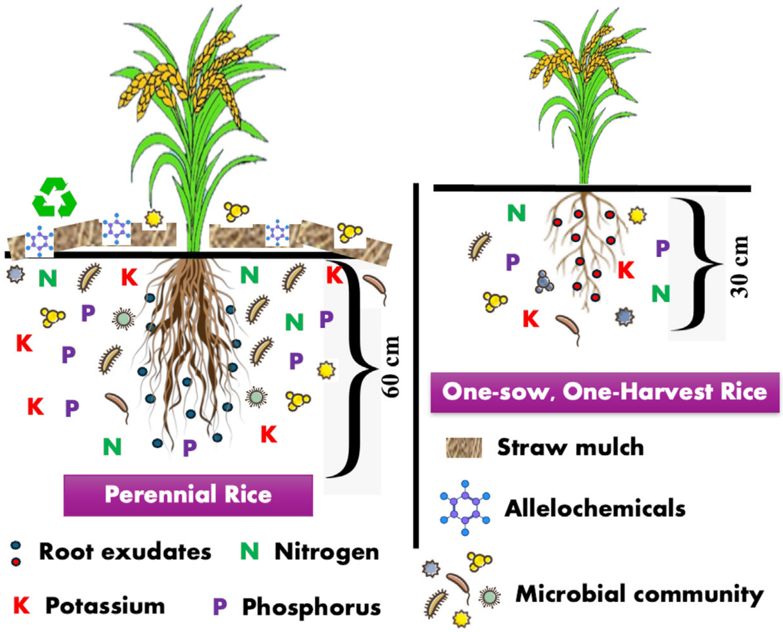
2.1. Benefits of perennial rice production system

2.1.1. Higher grain yield

The irrigated PR yielded an average of 6.8 Mg ha^{-1} $harvest^{-1}$ for eight consecutive harvests over four years after a single planting, slightly surpassing the 6.7 Mg ha^{-1} $harvest^{-1}$ achieved by seasonally replanted rice (Zhang et al., 2023). In a separate two-year field trial, Huang et al. (2018) evaluated PR23 at four locations in China, where it consistently yielded more than 13 Mg ha^{-1} $year^{-1}$. The grain yield was slightly higher in the first season than the second season across year and location due to factors like shorter growth duration and fewer panicles and spikelets in the second season. PR23 also showed strong regrowth potential, with a ratoon percentage between 90% and 98%, suggesting its suitability for commercial-scale production in irrigated environments. Zhang et al. (2019) further explored the influence of genotype-environment interactions on PR performance by comparing five PR genotypes with seasonal rice varieties across six growth cycles at seven locations in southern China between 2014 and 2017. Among these, PR23 stood out, yielding 5.25 Mg ha^{-1}, and maturing early (119 days, with only a 30-day variation across environments), while maintaining strong regrowth potential (82%). PR23 consistently outperformed seasonally replanted rice across diverse environments and growth cycles, highlighting its potential for high yield and resilience.

2.1.2. Carbon sequestration and reduced carbon footprint

The extended growth cycle of PR and no-tillage in the regrowth season, compared to annual rice, allows for continuous carbon uptake and storage (Hu et al., 2022). The sequestered carbon is incorporated into the soil's organic carbon pool, reducing atmospheric CO_2 levels and contributing to improved soil structure, water retention, and nutrient availability. Zhang et al. (2021) reported that PR cultivation significantly improved soil health, increasing soil carbon content by nearly 1 Mg ha^{-1} $year^{-1}$, N by 100 kg ha^{-1} $year^{-1}$, plant-available water capacity by 7.2 mm, and pH rose by up to 0.4 units, underscoring the positive environmental impact of the PR system (Fig. 3). Similarly, Hu et al. (2022) found that continuous PR cropping increased the soil organic carbon and total N



Parameters	Perennial rice	One-sow, One-harvest rice
Straw mulch	Yes	No
Nutrient recycling	Yes	No
Nutrient mining	Less	More
Allelopathy	Yes	No
Soil sickness	Yes	No
Root exudates	Yes	Yes
Nutrient leaching	Less	More
Soil erosion	Less	More
Carbon sequestration	More	less
Root	Rhizome	Fibrous
Microbial community	More diverse	Less diverse
Weed competitiveness	High	Low

Fig. 3. Comparison of perennial rice and one-sow, one-harvest rice production system.

at a rate of 0.81 and 0.11 Mg ha^{-1} yr^{-1}, respectively, in the 0–40 cm layer, largely due to the decomposition of rice stubble and crop residue, particularly in the top 10 cm. This positive trend is likely to continue and intensify with more cycles of PR cultivation. By increasing soil carbon, N, and pH levels, the PR system enhances soil quality, which is essential for long-term agricultural productivity.

2.1.3. Soil health and resilience

The permanent living cover, deep root system, and minimal soil disturbance of PR enhance soil health by minimizing erosion, reducing nutrient runoff, and improving soil organic matter (Hu et al., 2022). It improves water and nutrient retention, uptake, and carbon and N cycling in the soil (Zhang et al., 2023). PR can access nutrients more effectively from large volumes of soil, especially phosphorus from the subsoil, than the shallow-rooted seasonal rice (Vijayakumar and Padma, 2023). In PR systems, a decrease in the carbon-to-nitrogen (C/N) ratio in the topsoil may enhance microbial decomposition of organic matter, resulting in net N mineralization within the soil. Soil pH value is also improved in the PR system and falls within the optimal range (5.0–6.5) for rice nutrient uptake (including phosphorus, copper, zinc, and boron) and microbial activity (Hu et al., 2022). The soil properties like water holding capacity and capillary and non-capillary porosity are favorably influenced by PR in the long run. Less disturbance to the soil retains the soil structure and enhances the oxidative capacity of soil methane-oxidizing bacteria, which leads to a reduction in methane emissions by 55% compared to conventional plow-assisted cultivation (Xu et al., 2021).

2.1.4. Enhanced input use efficiency

PR maintains stable root activity across successive regrowth seasons, establishing a resilient root system capable of efficiently absorbing soil nutrients and water during regrowth periods (Pimentel et al., 2012). Compared to transplanted rice, PR requires less irrigation and thrives better during dry spells. Its deep and extensive root systems enable access to water from deeper soil layers, utilizing water inaccessible to shallow-rooted annual plants. Additionally, PR helps loosen deep soil, improving aeration and enhancing the soil's water and nutrient-holding capacity (Hu et al., 2022). In PR systems, the soil remains covered by plant canopy for an extended period, reducing direct sunlight exposure and soil moisture evaporation. Consequently, more water remains available for plant uptake. Moreover, PR cultivation eliminates the need for seasonal planting and water-intensive land preparation practices like puddling (Huang et al., 2018; Zhang et al., 2019). It also capitalizes on intermittent rainfall, reducing the reliance on external irrigation sources.

With its higher water use efficiency and reduced water requirements compared to transplanted rice, PR contributes to conserving groundwater and local water resources, making it particularly beneficial in regions facing water scarcity. The soil in PR is kept under crop cover, reducing soil erosion and promoting sustainable crop productivity in upland cropping systems (Fig. 1). Cultivating PR in the same piece of land for a longer time may induce mycorrhizal fungus activity by promoting a symbiotic relationship with plant roots, facilitating water and nutrient uptake (Guigard et al., 2023). Moreover, mycorrhizal fungi provide a glomalin (glycoprotein), which promotes soil aggregate stability, leading to more macro aggregates and improved soil structure as PR roots host more microbes than conventional rice cultivation (Li et al., 2022).

2.1.5. Labor and energy saving

Unlike transplanted rice, PR does not require frequent land preparation, such as ploughing, and puddling, as well as transplanting, which together account for about 43% of the total labor in transplanted rice cultivation (Zhang et al., 2023). Consequently, the need for machinery and human labor is reduced, leading to lower fossil fuel consumption, reduced input energy, and increased energy productivity (Huang et al., 2018). In fact, the labor input per growing season is reduced by 54% in the PR system (Dossou-Yovo et al., 2024). PR reduced labor demands by 68–77 days ha^{-1} per regrowth season, easing the workload for rural farmers, particularly women and children, without increasing reliance on fossil fuel-based mechanization (Hu et al., 2022). Similarly, Dossou-Yovo et al. (2024) reported a 29% reduction in the total annual labor input in the PR systems compared to the rice–rice system. Beyond labor savings, PR also reduces the need for inputs like seeds, irrigation, fertilizers, and pesticides, contributing to overall energy savings.

2.1.6. Economic advantage

PR offers significant economic advantages over transplanted rice, primarily due to its ability to reduce production costs by minimizing labor requirements and eliminating the need for tasks such as nursery preparation, seedling rising, field preparation, and transplanting. These factors result in substantial cost savings (Huang et al., 2018; Padma et al., 2023). Additionally, the decreased use of seeds, fertilizers, and pesticides further lowers production costs, enhancing the economic feasibility of PR cultivation. Despite yielding 8.8% less than the annual rice-rice system, PR still generated a net profit 235% higher (6114 CNY ha^{-1}) than the annual system (Zhang et al., 2021). Farmers are attracted to PR primarily due to the potential for reduced costs, particularly in terms of labor. A four-year study by Zhang et al. (2023) demonstrated that PR cultivation results in a 58.1% reduction in labor and a 49.2% decrease in production costs compared to seasonally transplanted rice. Dossou-Yovo et al. (2024) reported a 22% reduction in total production costs in PR systems compared to traditional rice-rice systems. Similarly, Hu et al. (2022) reported that the production cost was similar for both the methods (seasonal and PR) in the first season, while PR offered an economic advantage due to lower labor costs (US$ 1057-1206 ha^{-1}) and non-labor costs (US$ 96-201 ha^{-1}), resulting in savings of US$ 1177-1401 ha^{-1} (46.8–51% of annual rice costs) per ratoon compared to the first season.

PR offers the potential for higher cumulative yields compared to annual varieties due to its extended cropping duration, leading to enhanced economic returns and food security. Hu et al. (2022) conducted a four-year study across three locations (Mengzhe, Xinping, and Menglian) and found that while labor costs were comparable to annual rice in the first season (71.3–79.5% of total costs), PR offered significant savings in regrowth seasons by eliminating the need for seedling, plowing, and transplanting. As a result, the net economic benefits of PR in regrowth seasons were 882, 109, and 1165 US$ ha^{-1} $season^{-1}$, higher than seasonal rice at Mengzhe, Xinping, and Menglian, respectively. These amounts were 57.3%, 17.4%, and 161% higher than those of superior annual rice at Mengzhe, Xinping, and Menglian, respectively. Cost-benefit analyses across eight locations in Yunnan demonstrated significant improvements in labor efficiency and profit per investment unit with PR compared to annual rice. The ratoon crop of PR23 generated higher profits than the re-sown crop, as PR23 reduces investment costs by over 50%. This is due to the elimination of expenses related to seed purchase, nursery raising, transplanting, and land preparation after the first crop season (Huang et al., 2018). The success of PR23 serves as a model for future PR technologies, showcasing high-yield performance, preferred grain quality, labor savings, and substantial economic benefits (Huang et al., 2018; Zhang et al., 2023). In markets that prioritize eco-friendly and socially responsible practices, PR can command premium prices thanks to its reduced environmental impact and sustainable production methods. Additionally, PR is highly compatible with organic and natural farming practices, allowing rice farmers to gain carbon credits by adopting these sustainable methods.

2.1.7. Grain quality

The PR23 exhibited grain size and quality comparable to RD23, a popular annual cultivar. Additionally, PR23 milling quality was exceptionally high (73%), impressing both farmers and millers alike (Huang et al., 2018). PR23, PR24, and PR25 exhibit grain quality characteristics similar to the *Japonica* subspecies of *O. sativa*, likely inherited from their *O. longistaminata* parent. In contrast, PR101 displays grain quality traits resembling its *O. sativa* ssp. *indica* parent RD23 (Zhang et al., 2023). PR101 rice has a longer, thinner grain shape with a length/width ratio of 3.57. In contrast, PR23, PR24, and PR25 have a shorter, wider grain shape with a length/width ratio of 2.13. These grain qualities are generally preferred by consumers, except in countries like Tanzania, Ethiopia, and Laos, which have specific preferences for grain shape (Twine et al., 2022). The grain quality of PR also varies by location. For instance, PR23 achieved first-grade national standards for head rice recovery in the Jinghong region (550 m altitude), but only second-grade in the Menglian region (955 m). Similarly, PR107 ranked third grade in Jinghong but reached first grade in Menglian (Shi et al., 2020). These variations highlight the need to improve and stabilize the grain quality of PR across different environments.

2.1.8. Biodiversity and ecosystem services

Perennial systems mimic natural ecosystems more closely and support significantly higher biodiversity, including greater diversity in plants, methanotrophic bacteria, arthropods, and birds, compared to seasonal crops. Also, it outperforms annual systems in ecosystem services such as methane consumption, pest suppression, pollination, and the conservation of grassland birds. (Werling et al., 2014). This enhanced biodiversity has positive effects on pest and disease management, reducing the reliance on chemical inputs. Additionally, perennial systems provide other ecosystem services like improved soil erosion, reduced GHG emissions, and water purification (Zhang et al., 2023). Given its potential for resource conservation, biodiversity conservation, and enhanced ecosystem services, PR farming holds promise as a widely adopted method of rice cultivation.

2.1.9. Climate adaptation

One key aspect of PR is its ability to withstand environmental stresses such as drought, flooding, and temperature fluctuations (Soto-Gómez and Pérez-Rodríguez, 2022; Wang et al., 2024). The root system of PR is more resistant to nematodes (Sacks et al., 2006; Huang et al., 2018). Rhizomes are underground stems that act as storage organs for PR. They help PR survive harsh conditions by providing essential nutrients and energy (Fan et al., 2022). Additionally, the deep root system of PR enables it to access water and nutrients from deeper soil layers, making it more resilient to drought conditions compared to annual rice varieties (Kim et al., 2020; Soto-Gómez and Pérez-Rodríguez, 2022; Tong et al., 2023). This resilience to water stress is particularly significant in regions experiencing erratic rainfall patterns and prolonged dry spells due to climate change. Furthermore, PR exhibits tolerance to flooding, a critical trait in areas prone to inundation or waterlogging. Unlike annual rice, which may suffer significant yield losses or complete crop failure under flooded conditions, PR can survive submerged for extended periods and resume growth once floodwaters recede (Tong et al., 2023). This flood tolerance trait enhances the resilience of PR cultivation in flood-prone regions, reducing production risks and safeguarding food security.

In addition to water-related stresses, PR also demonstrates resilience to temperature extremes and fluctuations (Tong et al., 2023). As global temperatures continue to rise, agricultural systems are increasingly vulnerable to heat stress, which can adversely affect crop growth and productivity. PR possesses the ability to withstand temperature fluctuations and maintain growth under varying climatic conditions, enhancing its suitability for cultivation in diverse agroecological zones (Tong et al., 2023). Moreover, the extended cropping duration of PR provides a buffer against climate variability by allowing for flexibility in the timing and duration of harvests. Unlike annual rice, which has a fixed growing season and is susceptible to yield losses from unfavorable weather during critical growth stages, PR can adapt its growth and development to prevailing climatic conditions, reducing the risk of crop failure and yield losses.

3. Constrains in perennial rice cultivation

The concept of PR cultivation offers significant environmental, economic, and social benefits. However, realizing the full potential of PR systems requires overcoming a wide range of practical challenges discussed below.

3.1. Yield reduction in successive ratoons under specific agro-climatic conditions

PR yields around 70–80% of the previous year's crop, which necessitates efforts to achieve consistent yields across successive seasons (Dossou-Yovo et al., 2024). Additionally, PR exhibits yield fluctuations and yield instability across locations (Zhang et al., 2017, 2019). Therefore, maintaining consistent and high yields across different environmental conditions is a key challenge. For example, in West Africa, Dossou-Yovo et al. (2024) reported that PR varieties (PR101, PR107, PR23, PR24, and PR25) yielded 21% lower compared to rice-rice systems with local check (WITA9 and Sahel108), mainly due to significant yield declines in successive ratoons (on average > 80% from the fourth ratoon compared to the first season) caused by shorter growing seasons and reduced regrowth rates. The total grain yield of PR over multiple seasons was divided by the number of seasons, the average yield was only 2.4 Mg ha^{-1} season^{-1} (Dossou-Yovo et al., 2024). This is significantly lower than the average yield of 6.7 Mg ha^{-1} season^{-1} reported in China (Zhang et al., 2023). The lower performance of PR in West Africa could be due to the higher temperature regimes. High day-and-night time temperatures in West Africa compared to China's cold stress, particularly from December to February might have stressed the plants and limited their ratoon growth in West Africa (Jagadish et al., 2015).

3.2. Breeding constraints

The key traits for successful perennial rice cultivation are its perenniality, survival through the rhizomes, and higher yields. However, breeding for PR is a complex process that requires overcoming genetic barriers while maintaining high yield potential, disease resistance, drought or cold tolerance, particularly during the flowering stage in subtropical and temperate climates, along with other agronomic qualities (Sacks, 2014). Developing PR varieties for extreme weather conditions requires incorporating multiple, unlinked genes. However, these genes are currently unidentified to aid stress tolerance (Chapman et al., 2022). Unfortunately, only very limited information is available on the genetics underlying perenniality ability in rice. Furthermore, efforts at wide hybridization are often hindered due to chromosomal differences from varying genomic compositions, leading to moderate to complete sterility and reduced genetic recombination in subsequent progeny (Cox et al., 2002). For instance, although cultivated and *O. longistaminata* share a common genome (AA), crossing between them often leads to embryo abortion (Oka, 1988). The crossing also results in hybrid sterility due to multiple reproductive barriers, including the presence of lethality genes (Li et al., 2020). Another challenge of breeding is the linkage drag (for example, a high tendency for seed shattering) from undomesticated parents and the low frequency of desirable traits introgression to the progenies. Similarly, ensuring the tolerance of PR to prolonged or multiple dry periods is critical for maintaining minimal/optimal yields under rainfed lowland environments.

3.3. Water management

The lack of proper agronomic management practices, particularly water, weed, and nutrient management, limits the farmers to realize the full potential of PR. PR varieties like PR23 and PR25 in Mbe, Côte d'Ivoire, and PR107 in Ndiaye, Senegal, offer alternatives to the conventional rice–rice system, reducing labor demand and increasing profitability, but they require more water due to their longer growing periods (Dossou-Yovo et al., 2024). There is no specific irrigation management available for PR. As a result, the PR crop was managed the same as transplanted rice (3–5 cm of water throughout the season) in most cases, which resulted in a significant increase in irrigation water demand (Dossou-Yovo et al., 2024). Similarly, after the harvest of PR, it is recommended to provide irrigation to the field during the dry season to support regrowth. All PR varieties were able to survive the dry season with supplemental irrigation (Zhang et al., 2019), highlighting the need for additional water management in drier regions.

3.4. Weed management

PR may encounter fewer weed problems over time due to its higher competitive ability over one-sow, one-harvest rice. The use of straw mulch and the allelopathic effect of rice and rice straw from previous harvests can further suppress weed growth and development (Amb and Ahluwalia, 2016). However, significant weed interference still occurs, particularly due to the absence of water ponding in the early stages and the emergence of multiple weed flushes, especially after harvest (Soto-Gómez and Pérez-Rodríguez, 2022). Weed control during rice regrowth is challenging, as traditional weeding tools are less effective, and the lack of tillage exacerbates weed emergence (Stokstad, 2022). Additionally, uneven weed germination in PR and a shift towards perennial weed flora can reduce herbicide efficacy due to differences in weed age at the time of herbicide application. Zhang et al. (2023) reported that a higher application of herbicides is required in PR to control weeds in regrowth cycles than in transplanted rice. In West Africa, manual weeding was used instead of herbicides to manage weeds in PR. This practice undermined the main advantage of PR, which is reduced labor requirements (Dossou-Yovo et al., 2024).

Perennial weeds may also out-compete PR, creating competition for essential growth resources. Continuous mono-cropping of PR can alter the soil's physio-chemical properties, potentially causing soil sickness, while in-situ retention of rice stubble may produce toxic substances such as p-coumaric, p-hydroxybenzoic, syringic, vanillic, ferulic, and o-hydroxy phenyl acetic acids, that modifies soil microbial community and suppress weed growth and development (Ma et al., 2014; Meena et al., 2017). Therefore, developing improved weed-management agronomy and new selective herbicides capable of effectively controlling perennial weeds along with a wider window of applicability is essential.

3.5. Nutrient deficiency and allelopathy

PR is prone to nutrient deficiencies due to no-tillage after initial establishment, leading to nutrient depletion from the topsoil over multiple harvests. Existing nutrient management practices designed for single-season rice may not be suitable for perennial rice systems. In PR, the most important factor that influences the yield is the regrowth potential of auxiliary buds present in the rhizome to form tillers. A regrowth rate of more than 75 is critical for PR to obtain a reasonable yield (Zhang et al., 2023). Previous studies on seasonal rice have shown a positive link between N levels and tiller production (Subramanian et al., 2020). However, the relationship between N fertilization and regrowth of PR is not clear. Zhang et al. (2021) reported a negative relationship between N fertilizer and regrowth of PR, although increasing N levels from 120 kg ha^{-1} to 240 kg ha^{-1} leads to a significant increase in grain yield. In contrast, irrespective of the PR cultivar, Dossou-Yovo et al. (2024) reported a lower N fertilizer application (93 kg ha^{-1} at Mbe and 120 kg ha^{-1} at Ndiaye) in West Africa leads to a 49% decrease in regrowth rates across seasons.

China and India, two major rice-producing nations, overuse N fertilizers. China applies a substantial 180–240 kg ha^{-1} crop^{-1}, while India uses 100–150 kg ha^{-1} crop^{-1}. Increasing N fertilizer application from 180 to 240 kg ha^{-1} crop^{-1} in PR does not lead to a substantial boost in yield (Zhang et al., 2021). However, excessive use results in low N use efficiency (~35%), decreased economic profits, and increased environmental pollution (Rabalais et al., 2007; Tian et al., 2016). Based on four years of experiment, Hu et al. (2022) reported that PR cultivation leads to an increase in SOC and total N in the top 10 cm of soil. Similarly, PR root exudates may alter the microbial composition, reducing the biodiversity of root-associated bacteria and fungi (Andrews and Harris, 2000). Therefore, understanding PR soil nutrient dynamics and developing region-specific nutrient management practices are crucial.

3.6. Disease and pest pressure

The presence of pathogens loads in stubbles and host plants left after harvest heightens the risk of pest and disease outbreaks in PR (Fahad et al., 2021; Zhang et al., 2023). Extended growth cycles without breaks between harvests allow insect pests and diseases to persist and proliferate, leading to recurring infestations in successive crops (Stokstad, 2022). Pests such as the brown planthopper (*Nilaparvata lugens*) and green leafhopper (*Nephotettix virescens*) and viral diseases like tungro (Bacilliform virus), grassy stunt, and ragged stunt can cause severe infections in

PR (Vijayakumar et al., 2020). Additionally, fungal pathogens, including blast (*Magnaporthe oryzae*) (Pak et al., 2021), stem rot (*Sclerotium hydrophilum*) (Konthoujam and Chhetry, 2005), sheath blight (*Rhizoctonia solani*) (Singh et al., 2016), bakane (*Fusarium fujikuroi*) (Sasaki, 1976), and bacterial leaf blight (*Xanthomonas oryzae* pv. *oryzae*) (Niones, 2022) may accumulate, further increasing pest risks. Fertilizer management, particularly N plays a major role. Excessive N application could pose a threat to the PR system by increasing the incidence of pests and diseases (Zhang et al., 2023).

3.7. Harvesting challenges

Cutting height of rice crop is the most important factor which influences the ratoon regrowth. However, the optimum cutting height for PR is not clear. In China, the PR is cut at a height of 10 cm (Zhang et al., 2019), while in some other parts like West Africa, it is cut at 15 cm (Dossou-Yovo et al., 2024). Similarly, the optimum crop geometry for PR is not clear, especially if the crop needs to be harvested mechanically in every season. PR is planted similarly to seasonal rice with a crop spacing of 20 cm × 15 cm in China and 20 cm × 20 cm in West Africa (Zhang et al., 2019; Dossou-Yovo et al., 2024). The existing combine harvester use in PR may damage the mother plant, potentially hindering ratoon regrowth and ultimately reducing crop stand and yields. Therefore, crop geometry and cutting height of PR need to be tailored to its multiple growth cycles. This also highlights the need to investigate the impact of mechanized harvesters on the regrowth of PR. Also, the development of specialized harvesting equipment designed specifically for PR may be required. If PR is harvested manually, the primary benefit of reduced labor is negated (Dossou-Yovo et al., 2024).

A crucial aspect of PR is the number of times PR can be harvested before replanting. Studies in China generally indicate that PR can be harvested for eight seasons without substantial yield decline (Zhang et al., 2017, 2019, 2023; Huang et al., 2018; Hu et al., 2022). However, replanting becomes necessary after this period. In contrast, the PR system in West Africa experienced significant yield loss after two ratoons. Consequently, replanting is recommended for profitable rice production in West Africa after the second ratoon (Dossou-Yovo et al., 2024). Further research is needed to determine the maximum profitable number of ratoon crops and optimal harvest height for different regions.

3.8. Crop rotation challenges

PR limits crop rotation and increases the risk of soil sickness, such as the build-up of soil-borne pathogens, insects, and nematodes, depletion of mineral nutrients, and accumulation of toxic substances (Keneni et al., 2012; Stokstad, 2022). For instance, the repeated cultivation of mung bean has led to an increased population of the root-infecting nematode *Rotylenchulus* (Ventura et al., 1981). Similarly, the rice-wheat cropping system in the Indo-Gangetic Plains has experienced a decline in yield due to potassium depletion caused by continuous monocropping. Despite applying 120 kg of potassium per hectare annually, the potassium balance in this system remains negative, with a deficit of -99 kg ha^{-1} year^{-1} (Vijayakumar et al., 2024). Thus, PR may contribute to soil sickness and could lead to a decline in yields in the long term (Nie et al., 2008). However, at present, the long-term impact of PR on soil quality is not clear.

Another challenge is that PR reduces opportunities for crop diversification, particularly in small-scale subsistence farming. In regions like Asia and Africa, where farming is predominantly practiced by small and marginal farmers with less than 1 ha of land, diversified cropping is crucial for meeting household needs. This system spreads risk across multiple crops, minimizing the impact if one fails (Chhatre et al., 2016). However, PR limits diversification, thereby increasing the risk to farmers. Since PR is often promoted in terraced and labor-scarce areas, its adoption could also reduce land availability for other crops (Stokstad, 2022). Moreover, expanding PR onto marginal and degraded lands may further reduce the area available for cultivating pulses and oilseeds, potentially diminishing their production and posing a threat to food security.

3.9. Soil temperature and climatic constraints

In the long run, PR may alter soil temperatures, as decomposing crop debris temporarily raises soil temperatures. This temperature change can disrupt plant gravitropism, affecting rice rhizome development (Bastien et al., 2014). The gravitropic behavior of rice rhizomes (transition from buds to aerial stems) is influenced by soil temperature. In PR, higher temperatures (28–30 °C) promote greater rhizome growth compared to lower temperatures (17–19 °C), likely due to the influence of temperature on photosynthesis. At higher temperatures, photosynthesis is more efficient, resulting in increased sugar production that supports rhizome development (Moore et al., 2021). In contrast, lower temperatures lead to earlier upward rhizome growth (negative gravitropism) due to reduced photosynthesis (lower sucrose), which forces the rhizomes to grow upward early (Wang et al., 2024). Similarly, Fan et al. (2022) discovered that carbohydrates are crucial for the growth of rhizomes, and increasing the level of sucrose can slow down their upward growth.

While PR is resilient to adverse weather, it may not be ideal for regions with distinct summer and winter seasons, as prolonged winter can halt its growth and yield (Hu et al., 2022). Its suitability is mainly in areas with optimal temperatures for rice cultivation year-round, and the cropping system is rice-rice-rice, rice-rice-fallow, and rice-fallow system. Temperature is a key factor affecting the regrowth of PR. When the average temperature in January exceeded 13.5 °C, the regrowth rate remained above 75%, resulting in higher grain yields. However, when PR was exposed to temperatures of 0–4 °C for five or more days, the regrowth rate dropped significantly, leading to lower yields (Hu et al., 2022). Thus, a threshold temperature of 13.5 °C appears critical for harvesting PR, with an optimal regrowth rate of 75%. If these conditions are not met, substantial yield losses can occur. Interestingly, 2659 of 25, 049 global weather stations recorded suitable temperatures, suggesting significant global potential for PR around the world (Hu et al., 2022).

3.10. Economic benefits and labor efficiency

In West Africa, Dossou-Yovo et al. (2024) observed reduced profitability in the PR system compared to the seasonal transplanted rice-rice system, primarily due to a sharp decline in grain yield during successive ratoon seasons. In contrast, Zhang et al. (2023) reported that the PR system in China outperformed the rice-rice system in profitability, owing to stable grain yields and lower production costs in subsequent ratoon seasons. While PR systems require much less labor than transplanted rice, they produce less grain per unit of labor (labor productivity) (Dossou-Yovo et al., 2024). This means that even though PR systems are less labor-intensive, they are less efficient in terms of how much grain they produce per worker.

4. Path ahead

4.1. Development of PR with high yield, better grain quality, and pest & disease resistance

Two basic approaches are currently being used to develop PR *viz*. direct domestication and wide hybridization. While selecting candidate species for PR development, breeders need to look for traits such as longevity for multiple harvests without significant loss in productivity, pest and disease resistance, high yield, nutritional quality, high pollen fertility & seed-setting rate, tolerance to abiotic stress such as drought, flood, salinity, strong to moderately strong rhizome production and weed suppression potential among others (Zhang et al., 2023). To achieve the goal, the breeders need to use a combination of traditional breeding methods and modern technologies tools such as embryo rescue, genome editing, genome-wide association studies (GWAS), genomic selection, marker-assisted selection, mutagenesis, speed breeding, etc. These tools need to be utilized to identify and transfer gene(s) of perenniality from wild and weedy species into an existing rice cultivar without transferring the unfavorable genes of the wild rice. It is also important to combine genes (gene pyramiding) that provide resistance to pests and diseases, abiotic stresses, and good grain quality with perenniality genes to create a sustainable PR crop. The rice germplasm can be searched for resistant/tolerant donors and the resistance can be transferred to elite/popular varieties. PR varieties need to be adaptable to changing climate conditions. Varietal traits that perform well under various climatic scenarios are essential to ensure the resilience of PR systems.

Chromosome segment substitution lines (CSSLs) and gene pyramiding approach can be used to transfer gene(s) for perenniality (i.e. rhizome formation) in existing rice cultivars without transferring the unfavorable genes of the wild rice parent (Shim, 2012). Further, cutting-edge technologies and tools like marker-assisted breeding, CRISPR-Cas, and RNAi could accelerate the process of development of biotic stress-resilient plants. The PR variety PR23 was developed through hybridization by crossing *Oryza sativa* ssp. *indica* cv. RD23, an Asian domesticated annual rice with *O. longistaminata*, a wild perennial rice from Africa. The F_1 plant was rhizomatous with partial pollen fertility and self-compatibility, with this basic breeding material the way for the development of PR rice cultivars was paved. Five more PR cultivars PR23, PR57, PR129, PR137, and PR139 bred in China were presented in the proceedings of PR presented by Zhang in FAO (Zhang et al., 2023). The details of next-generation sequencing depict that the PR23 cultivar possesses 16.16% of its genome from *O. longistaminata* (Zhang et al., 2023).

The concept of using hybrids in PR is promising because hybrid rice typically exhibits heterosis (hybrid vigor), leading to enhanced yield potential, better disease resistance, and superior adaptability. If breeders can develop perennial hybrids that retain their regrowth ability and also capitalize on hybrid vigor, this could significantly boost the productivity of PR systems. Numerous national and international organizations, including The International Rice Research Institute (IRRI) in the Philippines and The Africa Rice Center in Côte d'Ivoire, are actively working to develop new varieties of PR. At the forefront, The Yunnan Academy of Agricultural Sciences (YAAS) in China, is actively spearheading initiatives to develop resilient PR strains capable of thriving in diverse environmental conditions (Zhang et al., 2018). Through innovative breeding techniques, YAAS is committed to developing PR varieties that can adapt to various environments, thereby promoting global agricultural sustainability (Zhang et al., 2018).

4.1.1. Candidate species for perennial rice development

The perenniality of grassy species is mainly derived from vegetative organs that can grow indefinitely, such as rhizome and stolon. The perennation in *O. sativa* occurs through the growth of axillary buds on older tillers, vegetative crowns, stolon, and rhizomes. According to Sacks et al. (2006) rhizomes can survive better than stolon comparatively in dry conditions and can help plants survive and spread. Among the different perennial wild rice, *Oryza rufipogon* (AA), and *O. longistaminata* (AA) belong to the *Oryza sativa* complex propagate vegetatively with stolons and rhizomes respectively. In contrast, the other species such as *O. australiensis, and O. rhizomatis* belong to the *O. officinalis* complex and are propagated vegetatively by underground stems (rhizomes). Several species are being explored for PR development. O. *longistaminata*, a wild rice species with exceptional heat, drought, and salinity tolerance, as well as lodging resistance, found valuable genetic resources for breeding programs (Tong et al., 2023). A list of potential perennial weedy rice species with their habit, chromosome number, genomic group, useful traits, and global distribution is provided in Table 1.

4.2. Developing new pest management strategies for perennial rice

To ensure the success and sustainability of PR farming, it is crucial to identify the key insect pests and diseases that threaten PR, along with their biology, such as modes of spread, and survival mechanisms. This understanding will allow researchers to develop effective pest management strategies. Breeding for genetic resistance to a broad range of pests and diseases is essential. Efforts should focus on enhancing the resistance of PR to these threats. Once perennial traits are established in a target rice variety, genes for disease resistance can be pyramided to strengthen pest

Table 1
Potential wild relatives of cultivated rice for perennial rice species for the perennial rice improvement: key characteristics, useful traits, and their global distribution.

Species	Habit	Chr No (2n =)	Genomic group	Useful traits	Distribution
O. alta	Vegetative crown	48	CCDD	Resistance to striped stem borer, high biomass production	Latin America
O. australiensis	Rhizomatous	24	EE	Resistance to BPH, BB, blast, drought avoidance, heat and drought tolerance, high amylose content, high gelatinization temperature	Australia
O. eichingeri	Vegetative crown	24	CC	Shade tolerance, resistance to BPH, GLH, and WBPH	Sri Lanka, Tropical Africa
O. grandiglumis	Vegetative crown	48	CCDD	High biomass production, weed competitiveness, flood and submergence resistance	South America
O. granulata	Vegetative crown	24	GG	Shade tolerance, adaptation to aerobic soil, BPH	South & South East Asia
O. latifolia	Vegetative crown	48	CCDD	Resistance to BPH, BB, high biomass production	Latin America
O. longiglumis	Vegetative crown	48	HHJJ	Resistance to blast, BB	Irian Jaya, Indonesia
O. longistaminata	Rhizomatous	24	AA	High pollen production, long stigma, heat, drought and salinity tolerance, lodging resistance, resistance to GLH, BB, blast, nematodes, source of CMS	Africa
O. meyeriana	Vegetative crown	24	GG	Shade and drought tolerance, adaptation to aerobic soil	South East Asia
O. minuta	Stoloniferous	48	BBCC	Resistance to BB, Blast, GLH, blast	the Philippines
O. officinalis	Rhizomatous	24	CC	Resistance to thrips, BPH, GLH, WBPH, BB, stem rot, tolerance to heat	Tropical and sub-Asia
O. rhizomatis	Rhizomatous	24	CC	Heat, drought and submergence tolerance, resistance to blast, BPH	Sri Lanka
O. ridleyi	VCS	48	HHJJ	Resistance to blast, BB	South East Asia
O. rufipogon	VCS	24	AA	Resistance to BB, blast, BPH, Tungro virus; moderately tolerant to SB, tolerance to aluminum, iron toxicity soil acidity, cold, salinity, heat, increased elongation under deep water; source of CMS and yield enhancing loci, high antioxidants	Tropical and Subtropical Asia, Tropical Australia
O. schlechteri	Stoloniferous	48	HHKK	Tolerance to flooding	Indonesia, Papua New Guinea

Abbreviations: Chr No-Chromosome number, O-*Oryza*, VCS-Vegetative crown and stoloniferous, BPH-brown plant hopper, GLH-green leaf hopper, WBPH-white backed planthopper, BB-bacterial blight, CMS-cytoplasmic male sterility, and SB-sheath blight, PNG-Papua New Guinea.

and disease resistance. This will reduce the risk of infestations and crop failures. Sustainable pest management, including integrated pest management (IPM) and bio-based IPM approaches, can mitigate the risk of crop failure and promote environmentally friendly and socially responsible farming. Biological pest control, using natural predators, parasites, and pathogens, offers a sustainable alternative to chemical pesticides. To control pests, diseases, and weeds, perennial rice could be rotated with legume pastures, brassica, or pulse crops (Zhang et al., 2023).

4.3. Developing better agronomy for perennial rice

Efficient and proper water management is key for successful ratoon crops in PR systems. The earlier research finding from ratoon rice revealed that flooding fields immediately after harvest helps in weed control, but it can lead to stubble rot, especially if the previous crop was cut close to the ground (Fig. 4). Additionally, it increases the risk of spreading insect pests and diseases (Krishnamurthy, 1988). To optimize ratoon development and tillering, it is recommended to delay flooding until the new tillers reach 10–15 cm in height (Coale and Jones, 1994). This approach allows the stubble to recover and reduces the risk of disease outbreaks. Given perennial rice's deep root system with multiple harvests (6–8), sub-surface drip irrigation could be a valuable technology to conserve water, labor, and energy while delivering nutrients through fertigation. This method also addresses nutrient deficiencies and minimizes weed problems in PR cultivation. Line planting of PR can solve both weed menace and irrigation water scarcity by enabling mechanical weeding and sub-surface drip irrigation. Since the regrowth dropped to below 75% and the yield significantly decreased, it is advised to resow PR cultivars every four years, ideally by direct seeding with minimal or no tillage, with the stubble clipped to a height of 10 cm and extra straw removed if needed for machinery passage (Zhang et al., 2023).

Another approach for managing weeds is developing herbicide-resistant PR. This will permit the use of broad-spectrum herbicides for weed control irrespective of the crop stage and ratoon. In PR cultivation, the height at which the crop is cut at harvest is crucial for maximizing regrowth. It is important to harvest the crop 10–15 cm above the soil surface (Dossou-Yovo et al., 2024). This practice increases the total available carbohydrates for ratoon regeneration. Research shows that cutting the main crop at ground level significantly reduces ratoon yields compared to harvesting at 50% of the main crop's height (Vijayakumar et al., 2020). However, a trade-off exists, while a higher cutting height promotes ratoon growth, it also increases the risk of insect and disease issues.

4.4. Nutrient management

PR mitigates nutrient depletion in topsoil as in-situ recycling straw through mulch increases soil organic matter, prevents soil erosion, enhances carbon sequestration, and improves nutrient retention, fostering greater biodiversity and climate resilience (Hu et al., 2022). However, research is needed to study the long-term effect of PR on soil nutrient balance. PR will require unique nutrient management strategies to supply plants with adequate nutrients over multiple growing seasons (Dossou-Yovo et al., 2024). Consider the following strategies for efficient nutrient management in PR cultivation: *Sub-surface fertigation:* The supply of essential nutrients through sub-surface drip irrigation will enable the precise delivery of essential nutrients to PR, optimizing nutrient use efficiency and reducing production costs (Subramanian et al., 2023; Ramesh et al., 2024). *Organic manure application in the sub-soil:* The application of bulky and concentrated organic manure deeper in the soil layer, preferably 45 cm below the crop rows before planting the crop, could improve the nutrient supply in the sub-soil. *Band placement of fertilizers:* Apply fertilizer near the crop base in the rows to enhance nutrient use efficiency (Su et al., 2015). The leaching loss of nutrients will be lower in PR, as the deep root system of PR increases the uptake of nutrients from the deeper soil layer. Special tools and implements may be developed to apply these fertilizers near the crop rows. *Foliar application of fertilizer:* Need-based foliar spray could help to correct any nutrient deficiency in PR. *Biofertilizer*: Tian et al. (2023) discovered that 11 bacterial strains from the *Enterobacter, Bacillus, Pseudomonas*, and *Kosakonia* genera could stimulate the growth of perennial rice seedlings. These strains may be valuable as biofertilizers to support the long-term productivity of perennial rice.

4.5. Economic viability

Assessing the economic feasibility of PR in different regions is essential. Initial research investments must be weighed against potential long-term benefits, such as reduced GHG emissions, inputs, and other ecosystem services. The economic assessment of the PR system should account for its GWP, as this system has the potential to reduce GHG emissions (Zhang et al., 2023). By reducing GHG emissions, farmers could earn carbon credits, which should be incorporated into the economic evaluation to offer a more comprehensive understanding of the system's benefits. Creating markets for PR, including offering premium prices or subsidies, can encourage adoption. With its water-energy-carbon efficiency, PR is well-suited for niche markets where eco-friendly products command higher prices, enhancing its economic viability. Long-term investments in research, similar to China's decade-long commitment, could open significant opportunities, though further development and dissemination will take time.

4.6. Identification and mapping of suitable areas

Among the environmental factors, temperature is the key factor determining PR regrowth. The region with average daily temperatures falling below 4 °C for more than five days and coldest-month averages dipping below 13.5 °C is not suitable for PR cultivation (Hu et al., 2022). Therefore, mapping suitable areas for PR cultivation is important. Terrace land under rice cultivation, degraded fallow lands, regions with rice-fallow or rice-rice cropping systems, and climates that support year-round growth can be suitable for PR. Other factors such as irrigation water availability, labor availability, labor wage, and production cost also need to be considered while demarcating suitable areas for PR cultivation. Technologies like remote sensing and GIS can aid in this process.

5. Conclusion

PR offers a carbon, water, labor, and energy-efficient alternative to traditional transplanted rice production, paving the way for a more sustainable and resilient agricultural future. Early findings from China showcase PR potential, with production costs and labor requirements reduced by nearly 50%. As a result, the PR area and the number of adopting farmers are steadily increasing in China. Although PR early results are promising, evaluations have largely focused on yield and economic benefits, overlooking other important impacts. A more comprehensive assessment of PR advantages should include its carbon and water footprints, energy efficiency, soil erosion mitigation, and broader ecosystem services such as biodiversity, pollinator populations (bees, birds), earthworm activity, and organic matter recycling to fully capture its environmental benefits.

However, maximizing PR potential outside of China presents significant challenges. The genetic complexities involved in developing PR varieties that consistently deliver high yields, grain quality, and resistance to pests and diseases demand innovative solutions. Good agronomic practices, including crop geometry, weed control, irrigation, nutrient management, and harvesting, must also be developed. Achieving these necessitates substantial investments in research and development as the current funding for PR remains limited. Increased financial support is essential to advance this promising agricultural innovation. Additionally, smaller-scale studies assessing PR socio-

Fig. 4. Rice field preparation for rice regrowth a) flooded field after rice crop harvest b) potential stubble rot issue.

economic impacts across different regions are needed before large-scale promotion. By addressing these priorities, we can pave the way for the widespread adoption of PR, contributing to a more sustainable agricultural landscape. Successful integration of PR into global agriculture holds the potential to transform food security while enhancing environmental sustainability.

CRediT authorship contribution statement

Vijayakumar Shanmugam: Writing – original draft, Methodology, Conceptualization. **Vikas C. Tyagi:** Writing – original draft. **Gobinath Rajendran:** Writing – original draft. **Suvarna Rani Chimmili:** Writing – original draft. **Arun Kumar Swarnaraj:** Writing – original draft. **Mariadoss Arulanandam:** Writing – original draft. **Virender Kumar:** Writing – review & editing, Supervision, Resources. **Panneerselvam Peramaiyan:** Writing – review & editing. **Varunseelan Murugaiyan:** Writing – original draft. **Raman Meenakshi Sundaram:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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