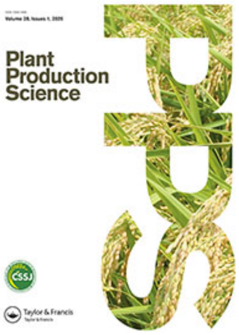

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History and progress in rice research and its future perspective in Cambodia

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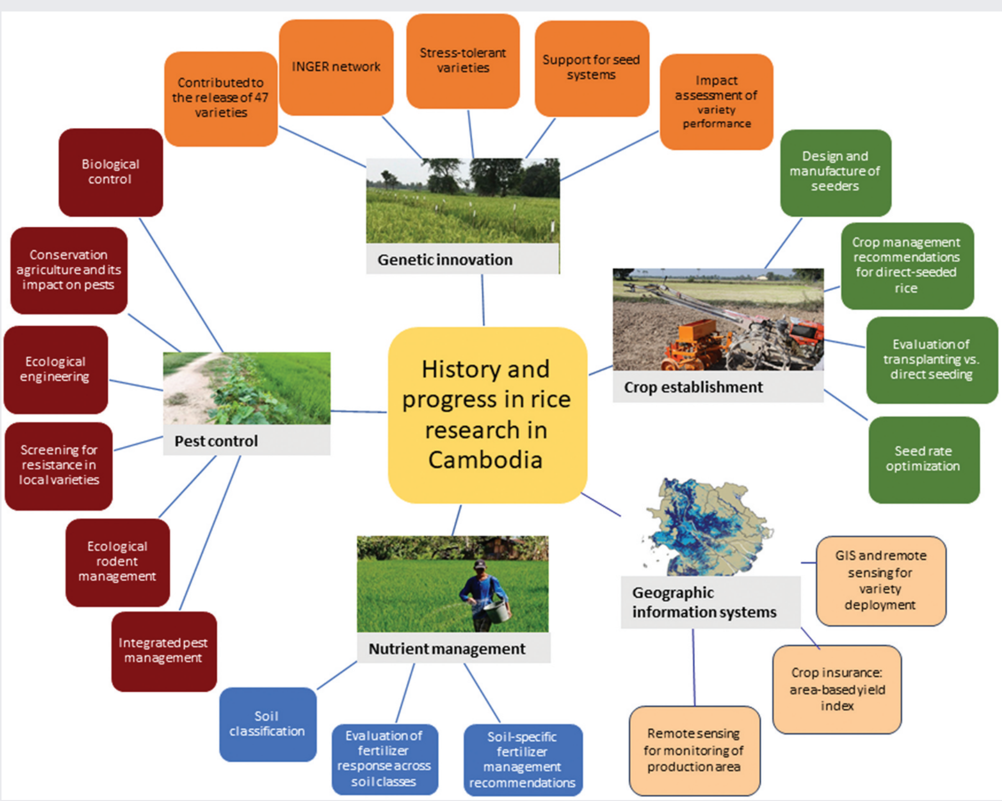
ABSTRACT

Since 1993, rice production in Cambodia has increased fivefold, positioning it as a key player in global food security through its export contributions. Considerable expansion of harvested area and its yield improvement have significantly boosted its production and export. Yet, with an average yield of 2.8 t/ha for rainfed lowland and 4.1 t/ha for irrigated lowland, there remains a substantial gap, highlighting the potential for further enhancements in productivity. This study aims to provide the current state of rice cultivation in Cambodia, the challenges it faces, history and progress in rice research, and future research directions focusing on genetic improvement and agronomy. Despite significant advancements, challenges such as climate vulnerability, sub-optimum crop establishment, soil and nutrient, and pest management practices persist, particularly in the dominant rainfed lowland rice systems. Rice varieties, fertilizer management practices, and pest control have been instrumental in addressing some challenges, yet ongoing research is crucial for developing solutions tailored to Cambodia's unique agricultural landscape. Future efforts must concentrate on developing climate-resilient rice varieties with high market value, sustainable soil and water management practices, and farm diversification options to fortify rice farming against climate change, thereby boosting productivity and sustainability.



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Introduction

Cambodia lies in the Mekong Peninsula of Southeast Asia. Rice cultivation forms the backbone of its agricultural sector, significantly contributing to its economic stability and global food security (Cosslett & Cosslett, 2018; Mund, 2011). It is the country's staple food, providing 65–75% of the population's energy needs (Global Rice Science Partnership GRiSP, 2013). Since 1993, rice production has increased five times in this country (Food and Agriculture Organization FAO, 2024). This significant growth in rice production has been attributed to expansion of harvested area as well as an increase in yield (Figure 1). Such area expansion has not been observed in the last decade in Thailand and Vietnam. In recent years, its rice yield has been higher than Thailand's. It became one of the major exporters with its export of more than 656,000 tons of milled rice in 2023.

Cambodia has a tropical monsoon climate; there is a rainy season, prolonged dry season, and irregular rainfall both from year to year and within years. Most rain falls from May to October. Rice is grown throughout the year, with wet season rice accounting for 75% of national production and dry season rice the remainder (Global Rice Science Partnership GRiSP, 2013). Annual water flow in the country is estimated at 472,000 million cubic meters, with 105,000 million cubic meters in the dry season (Asian Development Bank ADB, 2021). Only a fraction of this is utilized. Dry season rice is cultivated as irrigated lowland rice during the cropping period with full or supplementary irrigation or in receding floodwaters. Including irrigation, domestic, and other uses, only 7,000 million cubic meters of water is utilized for the dry season (Asian Development Bank ADB, 2021). The Ministry of Water Resources and Agrometeorology estimated that 24% of the agricultural areas are irrigated (MOWRAM, 2012; Resosudarmo & Chheng, 2021). Recent inventories of surface water irrigation show that out of roughly 4 million hectares, 273,767 ha are irrigated in the wet season, 260,815 ha in the dry season, and 29, 907 ha are irrigated in both seasons (Food and Agriculture Organization FAO, 2023). Wet season rice depends mainly on rainfall and is categorized further into rainfed upland, rainfed lowland, and deepwater (Cosslett & Cosslett, 2018; Sarom, 2007). Rainfed upland rice is grown in unbunded fields and mainly in the hill regions of northern and northeastern Cambodia. Deepwater rice is found mainly on the edges of lakes where the water is deep. Both of them form only a small proportion of the total rice area in this country (Makara et al., 2001; Sarom, 2007) and there has been limited research and development in these systems. Thus, we will not consider these production systems further in this paper. Rainfed lowland rice accounts for >90% of the total production area of wet season rice (Sarom, 2007). Rainfed lowland rice is found in all provinces, but mainly in the central plain around the great Lake Tonle Sap, which serves as the primary region for grain production, and on the lower streams of the Mekong and Bassac rivers.

Currently, the average yield of rainfed lowland rice at the national level is estimated at around 2.8 t/ha, while irrigated rice yields are higher at approximately 4.1 t/ha (Yuan et al., 2022). Among six countries in Southeast Asia (Cambodia, Indonesia, Myanmar, Philippines, Thailand, and Vietnam), Cambodia had the largest yield gap between biophysical potential and actual yield obtained in farmers' fields in both irrigated and rainfed rice systems (Yuan et al., 2022). In fact, rice yield at national level was the second lowest, following Thailand, among the

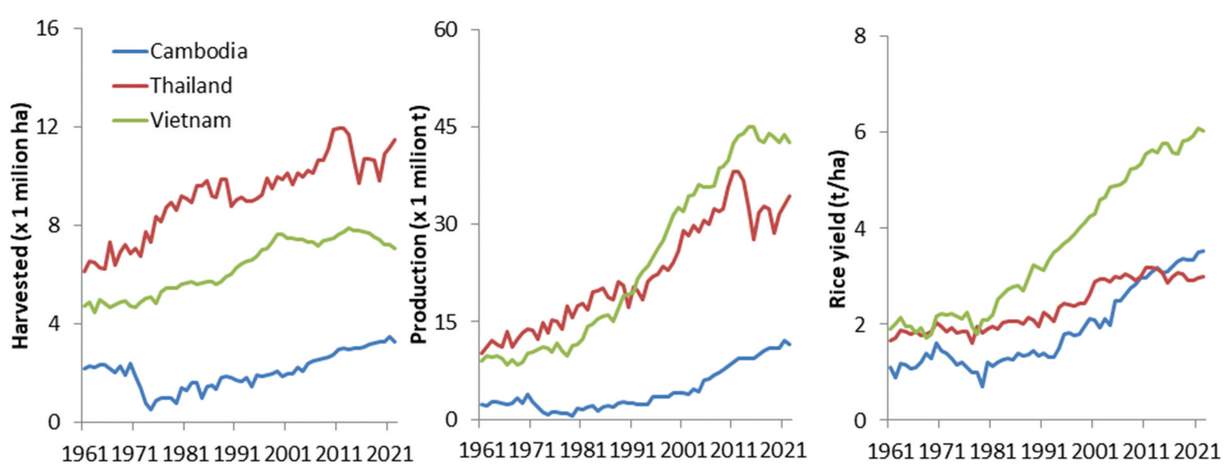

Figure 1. Trend in rice-harvested area (left), production (middle), and yield (right) in Cambodia, Thailand, and Vietnam (Food and Agriculture Organization FAO, 2024).

six countries. Therefore, there is a considerable yield gap in both systems, indicating a vast potential for further improvement of rice production. Given the projected 30% increase in global rice demand by 2050, Cambodia can play a critical role in ensuring global rice supply through its export capacity (Yuan et al., 2022).

This paper aims to provide the status quo of (i) current rice cultivation practices and challenges to rice production, (ii) selected achievements in rice research, and (iii) perspectives for future research on rice with focus on genetic improvement and agronomy. This paper focuses on research areas in genetic improvement, crop establishment methods, nutrient management, and pest control, which are the major focus of rice research in this country.

Rice cultivation practices

Rice production has transformed from subsistence to a market-oriented, intensive system in the last 30 years along with a fivefold increase in rice production (Food and Agriculture Organization FAO, 2024). Direct seeding for rice has spread in Southeast Asian countries, where economic transformation resulted in industry expansion, and thereby new employment opportunities in urban areas, leading to scarcity of farming labor and rising wage rate (Kumar & Ladha, 2011; Pandey & Velasco, 2002). This has pushed mechanization in agriculture, specifically for land preparation and harvesting (Chhun et al., 2015). The adoption of direct seeded rice has been increasing in Cambodia as the overall trend shown in studies in the 1990s and the 2020s (Table 1). The Ministry of Agriculture Forestry and Fisheries annual reports from 2012 to 2023 also confirm this trend. In the wet season, direct seeded rice accounted for around 70% and 98% in 2008 and 2020, respectively, whereas direct seeded rice accounted for almost 100% in 2009 and 2021 in the dry season, respectively. In Battambang province, however, Kamoshita et al. (2009) reported that direct seeded rice has also been commonly and extensively practiced in large fields having long distance from farmers' residences since the 1970s. The rising wage rate, increasing availability of chemical weed control methods, and water availability were considered to be the major driving forces (Pandey & Velasco, 2002). Adequate availability of water favors transplanting, whereas low water availability favors direct seeded rice. Moreover, puddling and transplanting require large amounts of water and labor, both of which are becoming increasingly scarce and expensive, making rice production less profitable. Also, the drudgery involved in transplanting – a job largely done by women – is of serious concern. Nursery and transplanting practices (including nursery preparation, seedling age, and transplanting density) varied considerably among farmers (Nesbitt, 1997). Seedling age at transplanting can depend on water availability in the main field, especially in the rainfed lowlands. The density was up to 800,000 hills/ha, whereas the recommended transplanting rate for modern varieties was at 250,000 hills/ha.

Table 1. Studies reporting adoption of direct-seeded rice in Cambodia.

Source	Region or province	Share of direct seeded rice
Elazegui et al. (1992)	12 provinces	20% adoption rate
Rickman et al. (1995)	Battambang	71% of farmers
Cambodia (1996)	Unknown	>30% of the rice-growing area
Jahn et al. (1996)	North-western Cambodia	11% and 32% of farmers in the wet and dry seasons, respectively.
Pandey and Velasco (2002)	Unknown	10% of area
Kamoshita et al. (2009)	Battambang	75–88% of area
Wang et al. (2012)	Northwest, Central, and South	93, 27, and 98% of area in early wet season, main wet season, and dry season, respectively
Flor et al. (2019)	Battambang, Kampong Thom, Prey Veng, and Takeo	87% of farmers in wet season, 99% of farmers in dry season
Castilla et al. (2020)	Battambang, Kampong Thom, Prey Veng, and Takeo	88% of fields
Khema et al. (2022)	14 provinces (Banteay Meanchey and Battambang)	75% of farmers (94% of farmers)
Touch et al. (2023)	Banteay Meanchey and Battambang	100% of farmers

In Cambodia, direct seeding is done mainly by manual broadcasting. There are two types of direct seeding: wet-direct seeding (in which sowing is done after puddling) and dry-direct seeding (in which sowing is done in dry fields without puddling) (R. Martin et al., 2020). Wet-direct seeding requires more water than dry-direct seeding because the field is puddled prior to seeding (Kumar & Ladha, 2011). Seeds are sown in a dry or slightly moist field, which is prepared similarly to fields for other crops. There are limited statistical data on direct seeding practices. According to a survey led by IRRI targeting 1,200 randomly selected rice farmers in 2023 (unpublished), 87% of farmers implemented direct seeding in the wet season, whereas 90% in the dry season. Of these farmers in the wet season, 53% implemented wet-direct seeding and 47% dry-direct seeding. In the dry season, 82% implemented wet-direct seeding and 18% dry-direct seeding.

The shift out of transplanting into manual broadcasting has changed other management practices. Farmers, who transplanted rice, were able to use water and hand weeding to control weeds; however, more reliance on herbicides came with the adoption of direct-seeded rice (Castilla et al., 2020). Farmers tended to use higher seed rates at 175–327 kg/ha in the dry season and 150–313 kg/ha in the wet season to compensate for poor seed quality, poor crop emergence, granivory by rodents, birds, and insects (Castilla et al., 2020; Flor et al., 2019; R. Martin et al., 2020). The use of high seeding rates also suppresses weed competition, but this seed is likely to be heavily contaminated with weed seeds, thus potentially exacerbating the weed problem (Chhun et al., 2020; Martin et al., 2017).

Farmers manage pests by relying on pesticides. The number of applications of insecticides, herbicides, fungicides, and rodenticides during the rice growing period ranged from 2 to 5, 2 to 4, 1 to 4, and 1 to 8, respectively (Flor et al., 2019). Furthermore, the majority of farmers rely on repeated use of a narrow range of post-emergence herbicides, thus leading to increased severity of weed problems in direct seeded rice (Martin et al., 2021). The uptake of early maturing varieties, improvements in irrigation, and expansion of rice cultivation in the margins of the lakes and rivers also resulted in an increase in cropping frequency (Jahn et al., 1996; Frost and King, 2003; Stuart et al., 2020). Alongside cropping asynchrony, this created favorable conditions for pests such as rodents (Castilla et al., 2020). Rodenticides are among the most widely used pesticides by Cambodian farmers (Flor et al., 2020).

Agricultural mechanization in Cambodia has been increasing widely since the 1990s especially in land preparation, irrigation, harvesting, and threshing. Mechanized land preparation and threshing accounted for approximately 12% rice-growing areas in the early 1990s (Nesbitt, 1997), and there was no combined harvester at that time. In 2015, mechanized land preparation, harvesting, and threshing accounted for 88%, 70%, and 98% of the total cultivated area, whereas planting, fertilizer application, and drying were still poorly mechanized as 1%, 1%, and 20% of the area (Department of Agricultural Engineering, General Directorate of Agriculture, 2016). Use of water pumps has also increased from 127,610 to 326,832 units over 10 years (2006 to 2015) in this country, although this figure is not specific to rice.

Farmers' adoption of inorganic fertilizer use has increased over 20 years. More farmers applied the fertilizer (97%) in 2019 than those in the previous study (Jahn et al., 1997) which reported that 70% and 83% of farmers used inorganic fertilizer in dry and wet seasons in 1995–1996, respectively. To the best of our knowledge, there were no survey reports available on farmers' inorganic fertilizer application rate for rice cultivation until recent years. Castilla et al. (2020) reported data from 4 provinces (2 districts per province) on average fertilizer application rate. District averages ranged from 44 to 109, 6 to 37, and 0 to 13 kg N-P-K/ha, respectively. Khema et al. (2022) showed an average fertilizer application of 42-11-9 kg N-P-K/ha from 12 provinces with a range between 0 and 96, 0 and 50, and 0 and 75 kg N-P-K/ha, respectively. Yuan et al. (2021) showed a similar level of N fertilizer application rate in Myanmar, Philippines, Thailand, and Vietnam. Application of organic inputs has been limited (Makara et al., 2001).

Constraints to rice production

Rice production in Cambodia faces a multitude of challenges that hinder its productivity and sustainability. These challenges include, but are not limited to, abiotic stresses, issues related to agricultural inputs, and knowledge and technology gaps (Table 2). Rice farming in Cambodia is predominantly rainfed and significantly affected by abiotic stresses, with climatic extremes at the forefront. Heavy rains in the dry season, flash floods, and river floods as well as longer dry spells in the wet season exacerbate the vulnerability of rice cultivation through disruption of the agricultural calendar and reduced yield stability (Bell et al., 2001; Nesbitt, 1997; Figure 2). Furthermore, these erratic weather patterns discourage farmers from investing in rice cultivation.

The availability of high-quality rice seeds, especially for direct seeding, is limited, resulting in increased seed rate for avoiding poor crop establishment. Limited access to high-quality seeds is among the key constraints mentioned by farmers, which also affects the uptake of new varieties (Vergara et al., 2023). Farmers were mostly using their own saved seeds (69%), or exchanged from other farmers (8%) and only 8% used certified seeds (Flor et al., 2019). Policy measures are currently being put in place by the government to support the seed system (Vergara et al., 2023). Poor land preparation and crop establishment practices further lead to nonuniform crop stands and increased weed pressure, resulting in low rice yield and labor productivity. Precision land leveling and mechanized direct seeding could help, but availability of these technologies is still limited. Also, farmers have financial constraints. As the majority of rice fields are rainfed, where it is difficult to manage water, and the land is not well leveled, the introduction of mechanized transplanting is also challenging.

Table 2. Selected constraints on rice production Cambodia.

Category	Main constraint	Main cause/issue	Reference
Abiotic stress	Climatic extremes	Heavy rains in dry season; flash flood, river flood in wet season; and longer dry spells in the wet season. Majority of rice farming is rainfed. Poor water control.	Nesbitt (1997); Bell et al. (2001)
	Soil-related constraints	Poor soil N, P, K and S supply capacity. Number of problem soils exist exhibiting characteristics of iron toxicity, acidity, and high salt concentrations.	Nesbitt (1997); White, Oberthur, et al. (1997); Bell et al. (2001); Bell and Seng (2003)
Input	Availability of high-quality improved rice seed	Low production of the seed	Global Rice Science Partnership (GRiSP), 2013); Vergara et al. (2023)
	No suitable variety for direct seeding	Inadequate funding for scientific agricultural research.	Rickman et al. (2001)
	Poor land preparation & crop establishment due to low uptake of mechanization in precision land leveling and crop establishment (transplanting, direct seeded rice)	Their availability in the local market and prices. Lack of a farm credit system. Transplanting: majority of rice fields are rain-fed ones which are difficult to manage water, and the land is not leveled. Labor migration	Department of Agricultural Engineering, General Directorate of Agriculture (2016); Rickman et al. (2001); C. Chhun et al. (2015)
	Low or sub-optimal use of fertilizer	Lack of a farm credit system. Uncertainty in rainfall. A limited knowledge.	Global Rice Science Partnership (GRiSP), 2013)
	Heavy reliance of farmers on pesticides	No or limited economic incentives to adopt ecologically based pest management approaches	Castilla et al. (2020); Flor et al. (2019)
Knowledge and technology	Sub-optimal natural resource management and crop management practices	Inadequate funding for scientific agricultural research. A lack of good and effective agricultural crop extension programs. A lack of funding.	Khema et al. (2022); Global Rice Science Partnership (GRiSP), 2013)

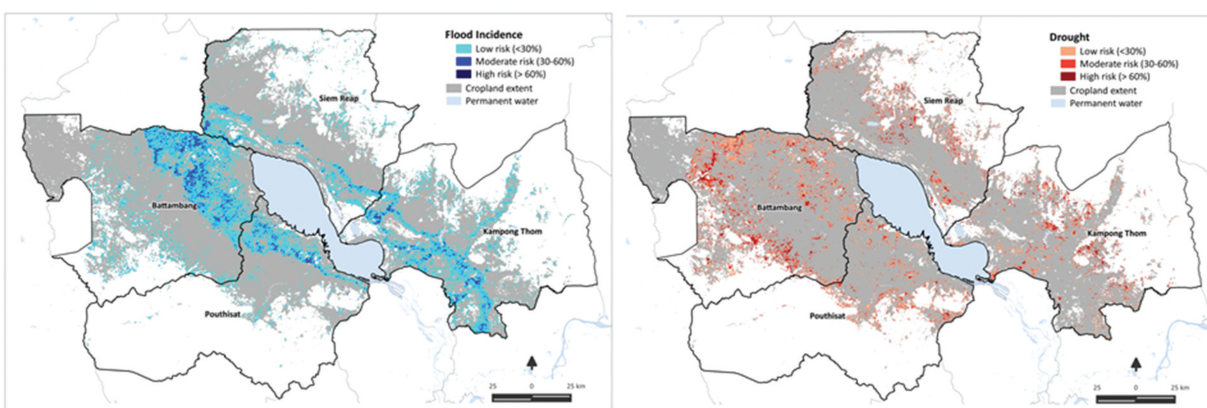

Figure 2. The maps showing areas with different levels of risks to flooding (left) and drought (right) (IRRI – ASTV Project, unpublished).

Most soils in the rainfed lowlands in Cambodia are infertile, and plant growth is generally limited by poor soil fertility together with fluctuating soil water regimes (Blair & Blair, 2014). They generally have low levels of nutrients, especially nitrogen (N), phosphorus (P), and, to a lesser extent, potassium (K) and sulfur (S) (Bell et al., 2001; Seng et al., 2001). Moreover, extreme fluctuations in soil-water levels due to climate extremes mentioned above can impair root activity, further restricting nutrient uptake. The resulting inefficient uptake apparently leads to weak responses to applied fertilizer. Low fertility results from strong weathering, low cation exchange capacity, low organic matter content, strong soil acidity, strong phosphate sorption capacity, and strong nutrient leaching or nutrient imbalances. About half of the rice growing areas in Cambodia consist of sands soils possessing such characteristics (Blair & Blair, 2014). Additionally, a number of problem soils exist, characterized by iron toxicity and salinity (White, Oberthur, et al., 1997).

Low or sub-optimal use of fertilizers has been driven by a combination of factors including the absence of a farm credit system, uncertainty in rainfall patterns, and limited knowledge among farmers (Global Rice Science Partnership GRiSP, 2013; Khema et al., 2022). Low use of inorganic fertilizer could also enhance soil nutrient mining. Farmers' heavy reliance on pesticides poses significant environmental and health risks (Castilla et al., 2020). Farmers' knowledge and technology gaps in natural resource, crop and pest management practices are reflected by inadequate funding for scientific agricultural research and a lack of effective agricultural extension programs.

Pests are significant threats to rice production, causing substantial damage and yield loss if not properly managed. An expert-based assessment of crop health has estimated that crop pathogens and pests can cause yield loss of up to 30% in rice (Savary et al., 2019). In Cambodia, published studies (Table 3) have shown the prevalence of key insect pests such as green leaf hopper (*Cicadella viridis*), brown plant hopper (*Nilaparvata lugens*) (CIAP (Cambodia-IRRI-Australia Project), 1992; Elazegui et al., 1992), stem borers (*Scirpophaga sp., Chilo sp., Sesamia inferens*), caseworm (*Nymphula depunctalis)*, brown plant hopper (*Nilaparvata lugens*), army worms (*Spodoptera sp*., *Mythimna separata*) (Jahn et al., 1997) in main rice producing provinces. During the period covered by these studies, diverse insect pests were not considered major problems due to high population of predators and parasites, infrequent use of pesticides and varietal diversity in farmers' fields are among the main reasons for the low pest problems (Nesbitt, 1997). A study by Castilla et al. (2020) covering the main rice producing provinces has shown that the insect pest problem is particularly notable compared to other groups of pests. Among the key insect pests observed were plant hoppers (*Nilaparvata lugens, Sogatela furcifera*), stem borer (*Scirpophaga spp*.), leaf folders (*Cnaphalocrocis medinalis, Hydrellia griseola*), and leaf hoppers (*Cicadella viridis*). The majority of farmers applied broad-spectrum insecticides including abamectin, a ready mixture of chlorpyrifos and cypermethrin, and emamectin benzoate (Table 3). Surveys targeting rice farmers in Battambang, Kampong Thom, Prey Veng, and Takeo have identified insects as the main pest, followed by diseases, weeds, rodents, and snails (Flor et al., 2020). Among the top insects causing damage in rice fields are stem borer, brown plant hopper, and rice leaf folder.

Studies from the 1990s have identified key diseases such as brown spot (*Cochliobolus miyabeanus*), bacterial blight (*Xanthomonas oryzae* pv. *oryzae*), leaf scald (*Monographella albescens)*, sheath blight (*Rhizoctonia solani*) (Elazegui et al., 1992; Jahn et al., 1997). Similar to insect pests, diseases were not considered a major problem (Jahn et al., 1997). In more recent studies, commonly observed disease prevalence include leaf blast (*Magnaporthe grisea*), bacterial blight (*Xanthomonas* pv. *oryzae*), red stripe (*Microbacterium sp*.), brown spot (*Cochliobolus miyabeanus*), and narrow brown spot (*Sphaerulina oryzina*) (Table 3) in Battambang, Kampong Thom, Takeo. To combat the diseases, farmers commonly applied fungicides tricyclazole, isoprothiolane, or ready mixture of tricyclazole and isoprothiolane (Castilla et al., 2020). In a study by Flor et al. (2020) Battambang, Kampong Thom, Takeo, and Prey Veng, brown leaf spot, bacterial leaf blight ((*Xanthomonas oryzae* pv. *oryzae*), rice blast (*Magnaporthe grisea*), and *bacterial sheath rot* (*Pseudomonas fuscovaginae*) are the key diseases in those provinces, and mixing different pesticides is common practice among rice farmers.

Weed is among the major pest problems, and rice yield losses due to weed competition can be larger than 20% (Chhun et al., 2020). Several main weeds identified in rice fields in the 1990s are umbrella sedges (*Cyperus difformis*), jungle rice (*Echinochloa colona*), broadleaf weed (*Alternanthera sessilis, Ipomoea aquatica*, *Monochoria vaginalis*), and grasses (*Brachiaria mutica*, *Ischaemum rugosum*, *Leersia hexandra*, *Panicum repens*, *Cynodon dactylon, Echinochloa colona, Echinochloa crussgalli, Paspalum distichum*). The majority of farmers use removal by hand as a control method (Elazegui et al., 1992; Jahn et al., 1997). Approximately two decades later, several species of weeds were identified in rice fields in Battambang, Kampong Thom, Takeo, and Prey Veng, where the majority of farmers addressed the problem using herbicides (Castilla et al., 2020; S. Chhun et al., 2020; R. Martin et al., 2020) mentioned that the shift into direct seeding in other Asian countries is associated with shifts in weed species composition. Moreover, in direct seeded rice areas in Cambodia, *Echinochloa* spp. and *Leptochloa chinensis* have become a problem.

Farmers also identified rodents as a problem in rice production (Castilla et al., 2020; Flor et al., 2020; Jahn et al., 1997), and they commonly use rodenticides. Rats can attack crops at any stage of growth, however, in particular attracted to the crops during the booting stage (Nesbitt, 1997). There are no studies associating the rise of rodent problems with direct seeding in Cambodia. Asynchronous crop establishment, weed problems, and severe rodent problems, however, are linked as key constraints in direct seeding in other countries (Ho & Romli, 2002). Flor et al. (2019) discussed cropping asynchrony in mostly direct-seeded rice areas in Cambodia. Thus, cropping asynchrony could potentially

Table 3. Prevalence of rice pests and control methods in various provinces in Cambodia.

Pest	Province	Farmer's control method	Reference
Insect pest			
Green leaf-hopper (*Cicadella viridis*) Brown plant hopper (*Nilaparvata lugens*) White-backed plant hopper (*Sogatella furcifera*)	Kum Prateah Lang (Phnom Penh) and rice areas around CARDI.	NA	CIAP Report (1992)
Green leaf-hopper (*Cicadella viridis*) Brown plant hopper (*Nilaparvata lugens*) Rice bug (*Leptocorisa acuta*) Caseworm (*Nymphula depunctalis*) Rice hispa (*Dicladispa armigera*) Rice leaf folder (*Cnaphalocrocis medinalist*) Whorl maggot (*Hydrellia spp.*) Rice gall midge (*Orseolia oryzae*) Stem borer (*Scirpophaga spp.*)	Banteay Meanchey, Battambang, Kandal, Kampong Cham, Kampong Chhnang, Kampong Speu, Kampong Thom, Phnom Penh, Prey Veng, Pursat, Svay Rieng, Takeo	NA	Elazegui et al. (1992)
Stem borers (*Scirpophaga sp./Chilo sp./Sesamia inferens*) Caseworm (*Nymphula depunctalis)*	NA	Removal by hand and insecticide	Jahn et al. (1997)
Brown plant hoppers (*Nilaparvata lugens*) Army worms (*Spodoptera sp./Mythimna separata*) Cutworms (*S. litura*) Greenhorned caterpillars (*Melanitis leda ismene/ Mycalesis sp.)* Caseworms (*Nymphula depunctalis)* Rice skippers (*Pelopidas mathias/Parnara guttata*) Semiloopers (*Naranga aenescnes*) Gall midges (*Orseolia oryzae*) Grasshoppers (*Oxya hyla intricata/Locusta migratoria manilensi/Hieroglyphus banian*) Stem borers (*Scirpophaga sp./Chilo sp./Sesamia inferens*)	Kandal, Kampong Speu, Svay Rieng, Phnom Penh, Takeo	Insecticides (>10%) mostly farmers in Kandal and Svay Rieng.	Nesbitt (1997)
Brown plant hopper (*Nilaparvata lugens*)	Takeo	Physical method: nets and beating Chemical method: mixed oil & ash, chemical pesticides	Matsukawa et al. (2015)
White-back planthopper (*Sogatella furcifera*)	Battambang, Kampong Thom, Phnom Penh	NA	Yin et al. (2017)
Leaf folder (*Cnaphalocrocis medinalis*) Leaf miner (*Hydrellia griseola*) Whorl maggot (*Hydrellia phipippina*) Stem borers (*Scirpophaga sp./Chilo sp./Sesamia inferens*) Planthopper (*Nilaparvata lugens, Sogatella furcifera*)	Battambang, Kampong Thom, Takeo, Prey Veng	Insecticides (abamectin, mixture of chlorpyrifos and cypermethrin, emamectin benzoate	Castilla et al. (2020)
Stem borers (*Scirpophaga sp./Chilo sp./Sesamia inferens*) Brown plant hopper (*Nilaparvata lugens*) Rice leaf folder (*Cnaphalocrocis medinalist*) Black bug (*Scotinophara coarctata*) Caseworm (*Nymphula depunctalis)* Grasshopper (*Oxya hyla intricata/Locusta migratoria manilensi/Hieroglyphus banian*) Rice bug (*Leptocorisa acuta*) Thrips (*Stenchaetothrips biformis*)	Battambang, Kampong Thom, Takeo, Prey Veng	Pesticides	Flor et al. (2020)
Disease			
Brown spot (*Cochliobolus miyabeanus*) Narrow brown spot (*Sphaerulina oryzina*) Bacterial blight (*Xanthomonas oryzae* pv. *oryzae*) Bacterial leaf streak (Xanthomonas pv. *oryzicola*) Leaf scald (*Monographella albescens*) Sheath blight (*Rhizoctonia solani*)	Banteay Meanchey, Battambang, Kandal, Kampong Cham, Kampong Chhnang, Kampong Speu, Kampong Thom, Phnom Penh, Prey Veng, Pursat, Svay Rieng, Takeo	NA	Elazegui et al. (1992)
Bacterial blight (*Xanthomonas* pv. *oryzae*) Leaf blast (*Magnaporthe grisea*) Brown spot (*Cochliobolus miyabeanus*) Leaf scald (*Microdochium oryzae*) Narrow brown spot (*Sphaerulina oryzina*) Sheath roth (*Sarocladium oryzae*) Sheath blight (*Rhizoctonia solani*)	Kandal, Kampong Speu, Svay Rieng, Phnom Penh, Takeo	NA	Jahn et al. (1997), Nesbitt (1997)
Leaf blast (*Magnaporthe grisea*) Bacterial blight (*Xanthomonas* pv. *oryzae*) Red stripe (*Micobacterium sp.*) Brown spot (*Cochliobolus miyabeanus*) Narrow brown spot (*Sphaerulina oryzina*)	Battambang, Kampong Thom, Takeo	Fungicides (tricyclazole, isoprothiolane or ready mixture of tricyclazole and isoprothiolane)	Castilla et al. (2020)

(*Continued*)

Table 3. (Continued).

Pest	Province	Farmer's control method	Reference
Brown leaf spot Bacterial leaf blight (*Xanthomonas oryzae* pv. *oryzae*) Rice blast (*Magnaporthe grisea*) Bacterial sheath rot (*Pseudomonas fuscovaginae*)	Battambang, Kampong Thom, Takeo, Prey Veng	Pesticides	Flor et al. (2020)
Weed			
Umbrella sedge (*Cyperus difformis*) Jungle rice (*Echinochloa colona*)	NA	Removal by hand	Jahn et al. (1997)
Broadleaf weed (*Alternanthera sessilis, Ipomoea aquatica*, *Monochoria vaginalis*) Grasses (*Brachiaria mutica, Ischaemum rugosum, Leersia hexandra, Panicum repens, Cynodon dactylon, Echinochloa colona, Echinochloa cruss-galli, Paspalum distichum*) Sedges (*Cyperus difformis*, *Eleocharis dulcis, Fimbristylis miliacea*, *Cyperus rotundus*)	Kandal, Kampong Speu, Svay Rieng, Phnom Penh, Takeo	Removal by hand (50%), herbicides (6%)	Nesbitt (1997)
Barnyard grass (*Echinochloa spp*) Red sprangletop (*Leptochloa chinensis*) Rice flat sedge (*Cyperus iria*) Water primrose (*Ludwigia adscendens*) Mexican primrose willow (*Ludwigia octovalvis*) Cockspur grass (*Echinichloa crus-galli*) Water primrose (*Ludwigia hyssopifolia*)	Battambang, Kampong Thom, Takeo, Prey Veng	Herbicides (quinclorac, pyrazosulfuron ethyl and fenoxaprop-p-ethyl, bispyribac sodium, 2,4-D dimethylamine)	Castilla et al. (2020)
Weedy rice (*Oryza sativa f. spontanea*) Hoorah grass (*Fimbristylis miliacea*) Jungle rice (*Echinochloa colona*) Cockspur grass (*Echinochloa crus-galli*) Saramollagrass (*Ischaemum rugosum*)	Battambang	Herbicides	S. Chhun et al. (2020)
Rats			
Rats	NA	Rodenticide	Jahn et al. (1997)
Rats	Kandal, Kampong Speu, Svay Rieng, Phnom Penh, Takeo	Rodenticides, mechanical barriers, traps.	Nesbitt (1997)
Black rat (*Rattus rattus complex*) Greater bandicoot rat (*Bandicota indica*) Little rat (*Rattus exulans*) Rice field rat (*Rattus argentiventer*) Ryukyu mouse (*Mus caroli*)	Battambang, Kampong Thom, Takeo, Prey Veng	Rodenticides	Castilla et al. (2020)
Rats	Battambang, Kampong Thom, Takeo, Prey Veng	Rodenticides	Flor et al. (2020)
Snails			
Golden apple snails (*Pomacea sp.*)	Svay Rieng	NA	Nesbitt (1997)
Apple snails (*Pomacea* spp.)	Lowland rice areas.	Molluscicides	Khay et al. (2018)

contribute to the rodent problems in direct-seeded rice areas. Golden apple snails were discovered in Cambodia in 1995 (Jahn et al., 1997). They were initially introduced as food for humans due to their high protein content but then escaped and became a rice pest, and since then this invasive species quickly spread to many provinces (Khay et al., 2018).

History and progress in rice research

The constraints on rice production in Cambodia, described in the previous section, have been multifaceted, involving environmental, economic, and social dimensions. Addressing these challenges requires a concerted effort from the government, agricultural researchers, and the international community to develop and implement integrated solutions that are sustainable, scalable, and suited to the local context. The collaborative endeavors of the International Rice Research Institute (IRRI), the Ministry of Agriculture, Forestry, and Fisheries (MAFF), and other stakeholders have been instrumental in addressing these challenges through the development and dissemination of improved rice varieties, improved crop, nutrient, and pest management practices, and labor-saving technologies. Collaboration between the Royal Government of Cambodia and IRRI led to capacity building and the collection and preservation of Cambodian rice germplasm. Through these efforts, IRRI was able to reintroduce 766 traditional varieties to the country in the 1980s (International Rice Research Institute IRRI, 2020). Meanwhile, during the late 1970s IRRI varieties such as IR36 and IR42 were introduced by the government (Cramb et al., 2020). The formal collaborative efforts started with the Cambodia-IRRI-Australia Project (CIAP), which has laid a solid foundation for rice research and development up to now. The CIAP began in 1987 with the aim of increasing the country's rice production and productivity of its rice-based production systems, and lasted for 14 years. In 2001, CIAP was replaced through the establishment of the country's own Cambodian Agricultural Research and Development Institute (CARDI). In the following sub-section, we describe a few key achievements in rice research and development in this country from the CIAP and afterward.

Genetic improvement

The CIAP embarked on breeding programs to develop improved rice varieties for the country's diverse rice growing environments. The project and subsequent, continuous breeding efforts contributed to 47 rice varieties released in Cambodia. This includes 2, 3, 16, 17, and 11 ones for rainfed upland, deep water, irrigated lowland/rainfed lowland with short duration, rainfed lowland with medium duration, and rainfed lowland with long-duration, respectively, as of early 2024 (Table 4). These rice varieties have a diverse crop duration (93–-193 days from sowing to harvesting, Khema et al., 2022) and include landraces, and those introduced and developed in this country (Table 4). Medium duration varieties, which are sensitive to photoperiod, flower between mid-October and mid-November in rainfed lowland rice (FAO, 2002; Uch et al., 2023). There are many commercially important varieties in this group, especially aromatic and premium-grain varieties. They were released in 1999 and later. Long-duration varieties are strongly photoperiod-sensitive, and they flower only after mid-November. In the dry season, short duration, high-yielding rice is mainly cultivated in the provinces of Takeo, Prey Veng, Kandal, and Kampong Cham. Among the released varieties, 16 IRRI-bred lines have been released in Cambodia.

IRRI also supports a global network for the evaluation of advanced rice breeding lines (https://www.irri.org/inger). The International Network for Genetic Evaluation of Rice (INGER) is an IRRI-supported global network for the evaluation of advanced pre-variety breeding lines. These lines are contributed by breeding programs at IRRI and National Agricultural Research and Extension Systems (NARES) partner organizations including Cambodia. According to the INGER documents (https://www.irri.org/inger), some 70,000 breeding lines have been developed by IRRI and NARES partners, with more than 1,300 varieties in rice producing countries that have IRRI-developed germplasm. In ASEAN alone, INGER evaluation has led to over 430 varieties being released. In Cambodia, 51% of varietal releases until 2007 can be directly or indirectly traceable to INGER (https://www.irri.org/inger).

In 2015, CARDI released CAR 14 and CAR 15 that originated from IRRI (CARDI, 2016). Vergara et al. (2023) reported that CAR14 is resistant to blast and drought, whereas CAR15 is resistant to blast and has moderate resistance to brown planthoppers. A survey of a total of 1,220 respondents in four provinces (Pursat, Battambang, Kampong Thom, and Siem Reap) revealed percent area coverage of the top six varieties as follows: Phka Rumduol (33%), IR504–04 (24%; not an officially released variety in Cambodia), Riang Chey (13%), CAR9 (6%), Sen Kra Ob 01 (6%), and Malis Praing (4%) (Vergara et al., 2023). Popular varieties varied by season. Six varieties were adopted by 69% and 97% of farmers in the wet and dry seasons, respectively. Another survey conducted in 100 rainfed lowland fields in 14 provinces in 2019 found that 37 lowland rice varieties in total were cultivated (Khema et al., 2022). Among them, popular varieties were Phka Rumduol (14%), Sen Kra Ob 01 (12%), and Riang Chey (10%). In the mid-2010s, high-yielding, stress-tolerant rice varieties including Phka Rumduol (flooding moderate tolerant variety) have successfully been piloted (Vergara et al., 2023). However, a major bottleneck for farmers' adoption of these varieties was sustainable seed production and low seed market price as well as marketability of stress-tolerant rice apart from aromatic rice varieties such as Phka Rumduol.

In 2018, IRRI collaborated with the General Directorate of Agriculture (GDA) to establish a supportive seed system in the country. The national seed law as well as a process towards a system to assess seed quality and enable farmers to access good-quality seeds was established (GDA and IRRI 2020a). A second volume, published under this seed strategy, includes the guidelines for varietal testing, as well as seed certification process (GDA and IRRI 2020b). These encapsulate the plans of the government towards an established and accessible source for quality rice seeds. The network involves government designated producers of foundation seeds, as well as public and private seed producers and cooperatives that can be trained to meet quality standards.

A landmark rice variety released in Cambodia is Phka Rumduol, which was chosen as the 'World's Best Rice' at five The Rice Trader World Rice Conferences – Bali in 2012, Hong Kong in 2013, Phnom Penh in 2014, Hanoi in 2018, Phuket in 2022, and Manila 2024. Phka Rumduol is premium aromatic rice and was developed in CIAP. Recent on-farm trials confirmed its good performance in a wide range of soil fertility conditions (Uch et al., 2023). Phka Rumduol was also identified as a flooding moderate tolerant variety (Vergara et al., 2023).

Crop establishment

With concern about potential yield penalty with direct seeding rice and interest in developing improved crop

Table 4. A list of released rice varieties in Cambodia (updated version from Ouk et al., 2017).

Variety Name	Year released	Line number or designation	Variety type (landrace, introduced, or bred in the country)	Rice growing environment (duration)*	Yield (t/ha)	Aroma (yes/no)
IR66	1990	IR 32,307-107-3-2-2	Introduced	RL/IR (short duration)	4.0–6.5	No
IR72	1990	IR 35,366-40-3-3-2-2	Introduced	RL/IR (short duration)	3.5–6.0	No
Kru	1990	IR 13,429-150-3-2-1-2	Introduced	RL/IR (short duration)	3.5–6.0	No
Rimke	1991	ITA 150	Introduced	RU	2.5–4.0	No
Sita	1991	ITA 257	Introduced	RU	2.5–4.0	No
Don	1991	HTAFR 77,022-45-3-2-1	Introduced	Deep water	2.0–4.5	No
Khao Tah Petch	1991	Khao Tah Petch	Introduced	Deep water	2.0–4.0	No
Teweda	1991	Tewada	Introduced	Deep water	2.0–4.0	No
Santepheap1	1992	IR 43,342-10-1-1-3-3	Introduced	RL (medium duration)	4.0–6.0	No
Santepheap2	1992	IR 45,411-40-2-1	Introduced	RL (medium duration)	4.0–6.0	No
Santepheap3	1992	OR 142–99	Introduced	RL (medium duration)	4.0–6.5	No
IR Kesar	1993	IR 48,525-100-1-2	Introduced	RL/IR (short duration)	4.0–6.0	No
CAR1	1995	Pram'bei Kuor-PPD 679	Landrace	RL (medium duration)	2.5–4.0	No
CAR2	1995	Sammbark Krarharm-PPD 597	Landrace	RL (medium duration)	2.5–4.0	No
CAR3	1995	Srar-aerm Cheab Chan-Germ. B-293	Landrace	RL (medium duration)	2.5–4.5	No
CAR4	1995	Chang Kaom Ropeak-Germ.90 B-528	Landrace	RL (long duration)	2.5–5.0	No
CAR5	1995	Karn-tuy Touk-PPD 156	Landrace	RL (long duration)	2.5–4.5	No
CAR6	1995	Seo Nam'ng-Germ. B-429	Landrace	RL (long duration)	2.5–5.0	No
CAR7	1996	Chungkung Kreal-PPD 723	Landrace	RL (long duration)	2.5–4.0	No
CAR8	1996	Phka Sla-PPD 364	Landrace	RL (long duration)	2.5–4.5	No
CAR9	1996	Srau Kul-PPD 86	Landrace	RL (long duration)	2.5–4.5	No
CAR11	1997	Barnla Phdau-PPD 367	Landrace	RL (medium duration)	2.5–4.5	No
CAR12	1997	Koon Trei Khmau-Germ. A-66	Landrace	RL (long duration)	2.5–4.5	No
CAR13	1997	Neang Minh Tun-PPD 375	Landrace	RL (long duration)	2.5–4.5	No
Baray	1999	IR 57,259-9-2-1-3	Introduced	RL/IR (short duration)	4.0–6.0	No
Chul'sa	1999	IR 56,383-35-3-2-1	Introduced	RL/IR (short duration)	4.0–6.0	No
Rohat	1999	IR Kesar-1	Introduced	RL/IR (short duration)	4.0–6.0	No
Rumpe	1999	IR 62,037-71-3-1-1-3	Introduced	RL/IR (short duration)	4.0–6.0	No
Popoul	1999	IR 49,830-7-1-2-1-3	Introduced	RL (medium duration)	4.0–6.0	No
Sarika	1999	IR 49,817-SRN-44-B-1-2	Introduced	RL (medium duration)	4.0–6.0	No
Phka Rumchek	1999	Neang Sar-1	Landrace	RL (medium duration)	3.0–5.0	Yes
Phka Rumchang	1999	KDML 105–1	Introduced	RL (medium duration)	3.0–5.0	Yes
Phka Rumduol	1999	Somaly-1771	Landrace	RL (medium duration)	3.0–6.5	Yes
Riang Chey	1999	Mooha Phal-1	Landrace	RL (long duration)	3.5–5.5	No
Sen Pidao	2002	IR 65,610-105-2-5-2-2-2-CIR-1	Introduced	RL/IR (short duration)	3.7–7.5	No
Phka Romeat	2007	Kroya-7	Landrace	RL (medium duration)	3.0–6.5	Yes
Phka Rumdeng	2007	Somaly-55	Landrace	RL (medium duration)	3.0–6.5	Yes
Pkha Chan Sen Sar	2009	Phka Khgnei-2	Landrace	RL (medium duration)	3.5–5.0	No
Damnoeb Sbai Mongkul	2013	Damnoeb Krapeu-6	Landrace	RL (long duration)	3.2	No
CAR14	2015	IR 06L164	Introduced	RL/IR (short duration)	4.2–7.5	No
CAR15	2015	IR 04N155	Introduced	RL/IR (short duration)	4.0–7.4	No
Phka Rumduol Prang	2015	Phka Rumduol-04	Landrace	RL (medium duration)	3.5–5.5	Yes
CAR16	2016	IR 10IL149	Introduced	RL/IR (short duration)	4.1–6.8	No
Phka Mealdei	2017	CIR 827-4-6-B42-1-28-3-1	Bred in the country	RL (medium duration)	3.5–5.5	Yes
Smach02	2017	Smach-02	Landrace	RL (long duration)	3.2–4.2	No
Sen Kra-Ob 01	2019	Sen Kra-Ob	Landrace	RL/IR (short duration)	3.9–4.9	Yes
Champei Sar-70	2022	Phka Rumduol x CNi9024	Bred in the country	RL/IR (short duration)	4.3	Yes
Neang Kra Ob	2023	Phka Rumduol x IR68109-B-90-2-1-5-1-1 × Sen Kra Ob	Bred in the country	RL/IR (short duration)	3.9–8.0	Yes
Kang Rey	2023	Japonica x IR504–04	Bred in the country	RL/IR (short duration)	5.8	No

*RL: rainfed lowland, IR: irrigated lowland, RU rainfed upland.

establishment method for direct-seeded rice, several researchers compared direct seeding and transplanting in field experiments in Cambodia (Ikeda et al., 2008; R. Martin et al., 2020; Mitchell et al., 2004; Rickman et al., 2001). All the studies reported that well-managed direct-seeded rice had similar grain yields to those of transplanted rice. Direct seeded rice required less labor to establish, and matured faster.

A study by Robins (2014) tested options for crop establishment by season, hydrology, and topography for Cambodian lowland rice systems, and provided recommendations on the suitability of mechanized dry- and wet-direct seeding options according to soil type, topo sequence, and season. A locally manufactured equipment, the seed drill was promoted through this project. Sandhu et al. (2021) found that tractor-driven

Table 5. Recommended fertilizer rate and its expected yield in the given soil type (CIAP Cambodia-IRRI-Australia Project, 1998), and data on actual fertilizer application rate and yield from on-farm survey (average across farmers in the given soil type) (Khema et al., 2022).

	N (kg/ha)	P (kg/ha)	K (kg/ha)	Expected or actual yield (t/ha)
Recommended fertilizer rate (CIAP, 1998)				
Prey Khmer	22	6	32	1.8
Prateah Lang	67	10	13	2.2
Bakan/Orung	70	28	17	3.2
Toul Samrong	86	13	8	4.0
Kampong Siem	90	8	0	3.4
On-farm survey (Khema et al., 2022)				
Prey Khmer (n = 18)	32	12	6	2.9
Prateah Lang (n = 39)	50	13	16	3.2
Bakan (n = 8)	32	7	3	2.8
Toul Samroung (n = 17)	43	14	7	3.5
Kampong Siem (n = 10)	34	3	0	2.4
Difference				
Prey Khmer	−10	−6	26	−1.1
Prateah Lang	17	−3	−2	−1.0
Bakan	38	21	13	0.4
Toul Samroung	43	−1	2	0.5
Kampong Siem	56	5	0	1.0

seed drills supported sowing at an optimum soil depth of 2–3 cm (Sandhu et al., 2021). Fukai and Mitchell (2019), however, pointed out issues around seedling emergence when using seed drills. Rice seeds that are drill-sown are placed at a depth with greater soil moisture than on the soil surface. This may help achieve better establishment and reduce weed problems compared with crops established by broadcasting. However, proper land preparation is critical for uniform establishment of the drill-seeded crops and for weed control. On the other hand, drill-seeding is not suitable in heavy clay soils, under wet soil conditions, and in fields that have severe weed problems. Nonetheless, the testing of this seeder was an important step towards supporting a locally manufactured rice drill for two-wheel tractors suitable for Cambodian conditions (Robins, 2014).

An experiment on seed rate with mechanized direct-seeded rice showed that 80–100 kg/ha seed rate was optimal to achieve maximum yield under rainfed lowland rice systems (Direct Seeded Rice Consortium DSRC, 2019). Furthermore, it shows the potential to reduce the seed rate from the current practice of 180–350 kg/ha to 80–100 kg/ha. This reduction in seed rate through mechanized direct-seeded rice can enable farmers to purchase good-quality seeds. Use of certified good-quality seeds can increase yields by 0.5 to 0.9 t/ha (12–-26%) (Direct Seeded Rice Consortium (DSRC), 2019; data from CARDI). Good land preparation, leveling, and presence of standing water were important for reducing weed burdens.

R. Martin et al. (2020) showed that drum seeding at 80 kg/ha had a similar yield to broadcasting at 180 kg/ha under wet conditions with better profitability. Xangsayasane et al. (2019) compared between CARDI technology package (e.g. additional irrigation) including the use of Cambodian drill seeder (note that seed drill is used when the soil is rather dry) (2) farmer practice including broadcasting for yield and economic benefit over two seasons. Mechanical seeder together with CARDI technology package clearly showed advantage with yield and profit gain of 0.5 to 1.5 t/ha and 70 to 236 USD/ha, respectively. These two studies clearly show the potential for the introduction of mechanized direct seeded rice. Hung et al. (2022) demonstrated economic benefit from the use of laser land leveling in Cambodia. As land leveling is essential for direct seeded rice, especially under dry soil conditions, this technology can help improve its performance.

Soil and nutrient management

Considerable efforts have been made in land classification, mapping, and fertilizer response trials over a number of years. A major, and significant, output from this phase of soil research was the development of a practical Cambodian Soil Classification system. This has enabled good communication between research, extension, farmer, and policy players involved in agriculture (White, Oberthur, et al., 1997; White et al., 2000). In this classification, soil groups are defined as a unit of morphologically similar soils, which occur at the same position in the landscape. For example, a black, cracking clay occurring on an old alluvial terrace is classified separately from black, cracking clay occurring on an expansive floodplain. Similarly, all soils with a deep sandy profile occurring on old alluvial terraces are grouped together. These broad criteria assume a link between topographic location and morphology with pedogenic processes (White, Oberthür, et al., 1997). Major soil groups include Prateah Lang (37% of total rice area), Bakan (18%), Tuol Samroung (16%), Krakor (11%), Prey Khmer (6%), Kbal Por (5%), and Kok Trap (3%). Prateah Lang and Prey Khmer are sandy soils generally having low total carbon and N, CEC, and cations (Seng et al., 2001). They tend to have low to moderate rice yields (White, Oberthur, et al., 1997). Bakan, Kok Trap, and Tuol Samroung have higher levels of total carbon, CEC, and clay with better response to fertilizers. Krakor soils could produce as much as 10 t/ha with dry season rice. The relationship between soil groups and Fertility Capability Classification (FCC), which has been commonly used for a quantitative assessment of the soil fertility constraints and providing guidelines for management, was presented in White, Oberthür, et al. (1997).

The recommended fertilizer application, so-called 'Soil-specific nutrient management' was formulated for particular soil groups based on the results of fertilizer trials conducted by the CIAP during 1992–1997 (CIAP Cambodia-IRRI-Australia Project, 1998) (Table 4). Up to now, the recommendation has been used. Recent study confirms the effectiveness of this recommendation, especially in Prateah Lang (Kong et al., 2019) and Prey Khmer (Kong et al., 2020a), as well as for dry season rice (Kong et al., 2020b).

Data on fertilizer application rate and actual yield obtained from the on-farm survey (Khema et al., 2022) were averaged in each soil type, and compared with the recommended fertilizer application rate (CIAP Cambodia-IRRI-Australia Project, 1998) (Table 5). Lower actual yield than expected yield was associated with N input in Bakan, Tuol Samroung, and Kampong Siem. In these soils, there is still scope for enhancing yield through more N application. In contrast, higher actual yield than expected yield in Prey Khmer was related to higher N and P input, suggesting that revising fertilizer recommendation would be needed in this soil. Apart from the recommended fertilizer application, numerous studies were conducted to test green manures, compost, rock phosphate, and crop rotation for improving soil fertility (e.g. CIAP, 1999; Pheav et al., 2005; Ro et al., 2016; White et al., 1999). Although considerable effort has been put into generating scientific evidence on what worked or not, and on-farm piloting, there has been scarce information on farmers' adoption of such technologies and their impact on soil fertility.

Pest management

In Cambodia and other Southeast Asian countries, farmers mostly rely on chemical pesticides to control pest infestations, but this can harm human health and the environment. Addressing the impact of climate change underscores the critical need to develop sustainable pest management strategies, emphasizing the importance of integrated pest management (IPM) and reducing reliance on pesticides. In the last decades, sustainable pest management technologies have been tested in Cambodia as summarized in Table 6. In the 1990s, rice varieties were screened for resistance to gall midge (CIAP project report, 1992). A study on ecologically based rodent management (EBRM) was conducted by Stuart et al. (2020) over two rice cropping seasons. With the tested methods (EBRM), the damage level is reduced 22–34% compared to non-treatment fields, and the rice yield is on average 20–32% higher in the treatment fields. An introduction of crop diversification strategies was evaluated by Sattler et al. (2021). Mung bean (*Vigna radiata*) and sesame (*Sesamum indicum*) were planted in the surrounding rice fields to attract pest natural enemies, a method commonly called ecological engineering. Based on replicated field study, abundance of parasitoids – a group of natural enemies, was higher in ecological engineering and control plots during wet season compared to the plots where farmers sprayed pesticides. This indicates the positive impact of non-pesticide application on beneficial arthropods. In a separate study, Chou et al. (2020) explored the efficacy of biological control, *Trichoderma harzianum* strain BTB 022, which is available as a commercial biological control product in Cambodian markets, in combination with the resistant/susceptible varieties against blast disease (*Pyricularia oryzae* Cavara). The application of *T. harzianum* demonstrated effectiveness in reducing leaf blasts and neck blasts on susceptible rice variety IR504–04, although its efficacy was variable, while using the Biological Control Agent (BCA) in combination with resistant varieties CAR14 is considered a sustainable method to reduce yield losses and address limitations on

Table 6. Eco-friendly rice pest management technologies tested in Cambodia.

Technology	Description	Target of pest	Reference
Rice varieties	Varietal screening for resistance to gall midge was performed for 31 varieties at Stung Meanchey, Phnom Penh.	Gall midge	CIAP project report (1992)
Ecologically-based rodent management	Maintain basic hygiene in field margins, synchronous planting, community rat hunts, no electric fencing, Community Trap Barrier System (CTBS), Linear Trap Barrier System (LTBS).	Rodents	Stuart et al. (2020)
Biological control + rice varieties	*Trichoderma harzianum* strain BTB 022 with resistant variety CAR14 *T. harzianum* strain BTB 022 with susceptible variety IR504	Rice blast (*Pyricularia oryzae* Cavara)	Chou et al. (2020)
Ecological engineering	Mung bean grown on the bund surrounding rice field	Overall insect pests	Sattler et al. (2021)
Conservation agriculture	Application of practices with no tillage and cover crop	Nematodes (*Meloidogyne spp. Hirschmanniella spp.*) and (*Meloidogyne graminicola*)	Masson et al. (2022)

fungicide use. Conservation agriculture (CA) has been tested as a method to control parasitic nematodes. A study by Masson et al. (2022) evaluated CA no tillage with a cover crop *Stylosanthes guianensis* (cv. *Nina*), versus conventional plow-based tillage with no cover crop and showed that CA practices reduced plant parasitic nematode abundance by 88% which demonstrates the efficacy of CA in controlling nematodes.

However, the adoption of IPM faces several challenges. Heavy reliance on pesticides due to perceived immediate benefits and lack of knowledge about risks hinder adoption of IPM by the majority of rice farmers (Flor et al., 2018, 2020; Matsukawa et al., 2016). In addition, limited access to technical knowledge, attitudes, and practices prevent rice farmers from implementing IPM practices effectively (Dunn et al., 2023). In the case of conservation agriculture (CA), in addition to limited technical knowledge, limited local services of CA machinery and water availability are among the main challenges to technology adoption (Hin et al., 2021). Flor et al. (2018) conducted a review of the technological system and evolution of IPM in Cambodia, consisting of policies and program reviews as well as a survey of farmers from Battambang, Kampong Thom, Prey Veng, ;lkPursat, and Takeo. The study found that interrelated agronomic practices, ecological conditions in farming communities, governance mechanisms, the structure around knowledge diffusion and the industry of technological options create reciprocal socio-technical dependencies on pesticide use.

Mapping and characterization of rice areas using GIS and remote sensing

Geographic information systems (GIS) and remote sensing have been used to map and characterize rice areas in Cambodia, particularly for abiotic stresses such as flood and drought. For example, the project on Accelerating the adoption of Stress-Tolerant Varieties (ASTV) aimed at deploying new varieties that can survive in flood or drought conditions used multi-temporal satellite imagery to map the level of risk for floods or droughts and guide dissemination of stress-tolerant rice varieties where they are needed the most in four provinces around the Tonle Sap Lake (Figure 2).

Moreover, as part of the Remote sensing based Information and Insurance for Crops in emerging Economies (RIICE) Project, higher resolution maps (20 m) of rice area and planting dates, and detailed rice yield estimates for the whole country and by season were developed (http://www.riice.org/; Nelson et al., 2014; Setiyono et al., 2019). Such information is useful for monitoring rice areas, targeting productivity enhancing technologies, and supporting the interventions during calamities that affect agricultural crops. Crop insurance solutions through area-based yield index insurance based on these satellite-derived products from RIICE were developed and tested in partnership with insurance providers. Other ongoing work includes participatory climate risk mapping and adaptation planning, and crop suitability mapping for crop diversification and to improve resilience of Cambodian farmers.

Conclusion and perspectives for future research

Rice farming in Cambodia has experienced remarkable growth since 1993, with production increasing fivefold due to expanded cultivation areas and enhanced yield. Despite this growth, substantial yield gaps remain, signifying untapped potential for further improvements in both rainfed and irrigated systems. The challenges to rice production in Cambodia are multifaceted, encompassing climatic vulnerabilities, sub-optimal farming practices, and limited access to advanced technologies. Over the decades, pest issues have persisted and threatened agricultural productivity. Pests such as brown planthopper, green leafhopper, stem borer, armyworm, bacterial blight, sheath blight, and leaf blast have been documented in various studies across rice-producing areas. Despite the prevalence of various pests, there has been limited research on integrated pest management (IPM) strategies tailored to local conditions. In contrast, this review highlights significant progress in genetic improvement and agronomic practices. Integrated approaches to management – combining improved varieties, optimized nutrient management, and pest control – are essential for advancing rice production sustainability in Cambodia. Such approaches have been piloted by Chhay et al. (2017), through farmer field school training. Future research should focus on developing resilient farming systems that incorporate climate-smart practices including water management, enhancing soil health, and reducing dependence on chemical inputs. Furthermore, strengthening agricultural extension services to disseminate knowledge and industry stakeholders to enable innovations to be accessible to farmers are crucial. These can empower farmers to adopt new technologies, thereby closing the yield gaps and contributing more effectively to global food security.

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