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Pathways to sustainable rice insect pest management: comparative IPM insights from Japan and Indonesia

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1 Introduction

Rice is the staple food for over half of the global population, with Asia accounting for nearly 87% of global rice production and consumption (FAO, 2023). Japan and Indonesia play key roles as major producers with strong cultural and economic dependence on rice. In 2024, Japan produced about 7.3 million tons of primarily *Oryza sativa* subsp. *japonica* from approximately 1.4 million hectares of paddy fields (e-Stat, 2025), reflecting domestic demand driven by tourism recovery and dietary shifts. Indonesia, Southeast Asia's leading and the world's third-largest rice producer (FAO, 2023), harvested about 53 million tons of mainly *Oryza sativa* subsp. *indica* from roughly 10 million hectares in 2024, sustaining food security for over 281 million people (Badan Pusat Statistik Indonesia, 2025).

Rice cultivation in both countries predominantly uses irrigated systems (Suozhu et al., 2020; Tirtalistyani et al., 2022), creating favourable conditions for pest outbreaks, notably brown planthopper (*Nilaparvata lugens* Stål) and rice stink bugs. Chemical insecticide is one of the primary pest control tools in Japan and Indonesia (Katayama et al., 2015; Effendy et al., 2021). However, their excessive use has led to environmental pollution, residue accumulation, and the development of insecticide resistance, which harm non-target species and reduce biodiversity, thereby posing sustainability challenges (Thorburn, 2015; Nimako et al., 2023; Putri et al., 2023; Wan et al., 2025a). To address these issues, integrated pest management (IPM) has been promoted as a balanced approach combining biological, cultural, physical, and chemical methods (Tsushima, 2014; Thorburn, 2015; Wan et al., 2025b).

This article compares IPM implementation and pesticide regulatory frameworks in Japan and Indonesia, emphasizing water-soluble systemic insecticide use like neonicotinoids in rice cultivation. It examines associated environmental water contamination and pest resistance development, and discusses policy and operational drivers of insecticide application. The analysis concludes with strategies to reduce synthetic insecticide reliance in both countries to enhance sustainable rice production.

2 Integrated insect pest management and insecticide use in rice fields

Japanese IPM has largely been government-driven through financial support and policy promotion (Tsushima, 2014). Research on IPM practices began in the 1980s, and official guidelines were later issued by the Ministry of Agriculture, Forestry and Fisheries in the 2000s (Tsushima, 2014). The Japanese IPM framework comprises three stages: prevention (e.g., cultural control, crop rotation, resistant varieties, seed disinfection, pheromone or natural enemy use), decision (outbreak forecasting and production surveys), and control (biological, physical, and chemical methods) (MAFF, 2011).

Japan's regulatory framework for agricultural chemicals includes pesticide registration under the Agricultural Chemicals Regulation Act (MOE, 2025a), water pollution standards (MOE, 2025b), and maximum residue limits in crops (JFCRF, 2025). These measures aim to minimize health and environmental risks and have led to stricter pesticide regulations. Despite this, chemical insecticides still dominate crop protection, accounting for about 95% of pest control measures (FAO, 2025). Contributing factors include the temperate climate favouring pest persistence, farmers' risk-averse preference for zero pest damage, and historical subsidies supporting intensive control practices.

Japan's rice production has relied heavily on chemical pest control since the post–World War II period (Katayama et al., 2015). About half of all pesticides used nationally are applied to paddy fields (Furihata et al., 2019), at an average rate of approximately 12 kg/ha (FAO, 2025). In past decades, rice fields reportedly received up to 10 pesticide applications per crop cycle, including an average of 3–4 insecticide treatments during the growing season (Kiritani, 1977). Neonicotinoids represent the predominant class of insecticides used in Japanese rice farming, with average annual shipments of 411 tons recorded between 2013 and 2022 (NIES, 2025). Among these compounds, currently dinotefuran is the most extensively applied, followed by clothianidin (NIES, 2025).

Meanwhile, during the Green Revolution, Indonesia experienced severe pesticide overuse and widespread brown planthopper outbreaks, prompting a 1986 presidential decree banning 57 pesticide brands used in rice (Fakih et al., 2003). This action led to the establishment of a nationwide IPM program in 1989, supported by the Food and Agriculture Organization (Fakih et al., 2003; Thorburn, 2015). The program centred on agroecosystem concepts, implemented through Farmer Field Schools (FFS) that empowered farmers as IPM experts through experiments and season-long experiential learning to shape decision-making (Thorburn, 2015). It enhanced farmers' understanding of pest ecology, natural predator conservation, healthy crop growing, weekly field observation, and economic threshold–based pesticide use (Fakih et al., 2003; Thorburn, 2015). By the end of this program in 1999, over one million rice farmers had completed FFS training, leading to a marked decline in pesticide misuse and pest outbreaks (Thorburn, 2015).

Currently, the farmer active participation in rice cultivation remains central to Indonesian IPM. The Ministry of Agriculture implements IPM through seven components: (1) physical control (e.g., trap setting), (2) mechanical control (e.g., manual egg collection, pruning), (3) cultural control (e.g., crop rotation, trap or repellent plants), (4) pest-resistant crop varieties, (5) biological control (e.g., natural enemies), (6) regulatory and quarantine measures to prevent pest spread; and (7) chemical control (synthetic insecticides) as a last resort (Ibrahim et al., 2024). Farmers are also guided by six "tepat" (right) principles of insecticide use (right target, quality, type, time, dosage, method) to ensure safety and efficacy (Moekasan and Prabaningrum, 2021).

However, after the decline of government-supported IPM and FFS programs, insecticide use rebounded, with farmers relying more heavily on chemical control due to pest resistance and pressure for high yields, although other safer alternatives remain in use (Thorburn, 2015; Prihandiani et al., 2021). On average, Indonesian rice farmers apply insecticides 2–4 times per growing season, with total insecticide consumption for all crops averaging 163,868 tons annually from 2014 to 2023 and an overall pesticide use of 7 kg/ha, approximately half that of Japan (FAO, 2025). In Indramayu, one of the country's major rice-producing regions, imidacloprid and thiamethoxam are the most commonly used neonicotinoids by farmers (Putri et al., 2022).

3 Water pollution and impacts on ecosystems

Japan has documented pesticide contamination across environmental waters, primarily driven by runoff from chemically intensive rice paddies. The cooler, drier temperate climate of Japan likely prolongs insecticide persistence relative to tropical regions like Indonesia, facilitating residue accumulation (Sanchez-Bayo and Hyne, 2011; Daam et al., 2019). These chemicals were detected in surface waters (Sato et al., 2016; Hano et al., 2019; Hayashi et al., 2021; Sugino et al., 2023; Luo et al., 2026), with concentration reaching 1.9 µg/L in Akita, the third highest rice-producing region in the country (Luo et al., 2026). Shallow and deep groundwaters also contained neonicotinoids (up to 0.1 and 0.07 µg/L, respectively) (Putri et al., 2025a). They were even found in rainwater (up to 0.00079 µg/L) despite low volatility, likely due to aerial spraying method widely used in Japan (Putri et al., 2025b). Although these concentrations remained below Japanese water quality benchmarks (MOE, 2025b), they exceeded EU limits for both acute and chronic exposure (0.2 and 0.0083 µg/L, respectively).

Neonicotinoids exert strong direct toxicity on many non-target aquatic invertebrates and can indirectly alter higher taxa communities by disrupting food webs and ecosystem functions (Schmidt et al., 2022; Barmentlo et al., 2025). Sublethal exposures impair navigation, foraging, reproduction and immunity, which can result in the reduced colony performance and population declines (Morrissey et al., 2015; Strouhova et al., 2023). Neonicotinoid contamination in Japan has been linked to declines in aquatic insect populations, such as dragonflies, which are recognized as bioindicators of freshwater ecosystem health (Nakanishi et al., 2018). Reductions in zooplankton abundance have also been observed, resulting in diminished harvests of eel and smelt in Lake Shinji (Yamamuro et al., 2019). Contaminated environmental waters have also affected tap water quality (used as drinking water in Japan) in some areas (Sato et al., 2016; Kamata et al., 2020; Putri et al., 2025a; Luo et al., 2026), with tap water in Akita containing neonicotinoids up to 0.87 µg/L (Luo et al., 2026), raising concerns over chronic human exposure.

Indonesia also faces challenges, especially in recent years with rising insecticide use and increased mixing practices (Thorburn, 2015). In Indramayu, neonicotinoids rank among the three most used insecticides, yet their concentrations in surface water remained relatively low (up to 0.065 µg/L during rice maturation) and undetected in groundwater (Putri et al., 2022, 2023) compared to Japan. Nevertheless, high levels of banned insecticides, including hydrophobic aldrin (37 µg/L), heptachlor (20.7 µg/L), profenofos (12,070 µg/L), and hydrophilic aldicarb (50 µg/L), had been detected in surface waters, exceeding national water quality standards (Kadim et al., 2013; Suryono et al., 2019; Maksuk et al., 2021; Oginawati et al., 2021). Such insecticide application has been associated with declines in natural predator abundance and arthropod diversity in the country (Prihandiani et al., 2021; Dewina and Choesin, 2024).

4 Pest resistance due to chemical insecticide use

The repeated use of single-chemical insecticides in Japan has accelerated resistance development in major pests such as the brown planthopper. Rising resistance has reduced control efficacy, leading to increased application frequency or a shift toward newer insecticides. Resistance to neonicotinoids in brown planthopper populations increased up to 616-fold between 1992 and 2012 (MAFF, 2013). High resistance levels were recorded for imidacloprid, a neonicotinoid compound (LD_{50} from 0.73 µg/g in 2005 to 273.51 µg/g in 2017), and thiamethoxam, another neonicotinoid compound (LD_{50} from 0.27 µg/g in 2006 to 14.69 µg/g in 2017) (Fujii et al., 2020), prompting substitution with other two neonicotinoids (dinotefuran and clothianidin) to manage resistance.

In contrast, Indonesia's early Integrated Pest Management (IPM) program controlled pest resistance by emphasizing ecological approaches and restricting insecticide use to threshold-based applications (Thorburn, 2015). However, increased insecticide reliance after 2002 led to widespread brown planthopper outbreaks (Prihandiani et al., 2021), expanding affected rice areas from a few thousand hectares in the early 2000s to over 200,000 ha between 2008 and 2011 (Thorburn, 2015). This surge reflected both declining natural enemy populations and emerging resistance. Field monitoring in 2013–2014 detected imidacloprid resistance in brown planthopper populations from Karawang (resistance factor (RF) value of 108) and Indramayu (RF = 9) (Surahmat et al., 2016), while moderate resistance (RF = 12.7) was also observed in Subang (Baehaki et al., 2016). Overall, imidacloprid resistance levels in Indonesia remain lower than those reported in Japan.

5 Recommendations towards sustainable rice cultivation

Japan continues to rely more heavily on chemical insecticides for rice cultivation than Indonesia (FAO, 2025), even though its rice production is about one-seventh that of Indonesia. As a technologically advanced agricultural nation with strong consumer safety standards, Japan is well positioned to transition toward a more sustainable rice agroecosystem. The following strategies may support this transition:

1. Enhance farmer education and IPM extension. Farmer understanding of IPM in Japan remains limited, with insufficient community involvement (Tsushima, 2014). Scaling up training programs similar to Indonesia's FFS could strengthen farmers' skills in pest monitoring, natural enemy conservation, and threshold-based insecticide use. Assigning agricultural extension officers to each ward within municipalities to work directly with farmers and conduct regular trainings and field visits, as practiced in Indonesia (Cahyono and Agunga, 2016), would further facilitate direct farmer outreach, capacity building, and rural development.
2. Promote companion planting. In Japan, rice bunds are frequently treated with herbicides such as glyphosate to suppress weeds that are regarded as potential hosts of pests and diseases (Figure 1). In contrast, in some areas in Indonesia, farmers intentionally grow specific companion or refugia plants along rice bunds to attract natural predators and parasitoids while deterring pest populations (Amanda, 2017; Rosida et al., 2025). Farmers also practice an intercropping system, called 'tumpang sari' in Indonesia, in which rice is cultivated alongside secondary crops like corn and soybean (Taufik et al., 2019). These intercrops not only offer food and shelter for natural enemies but also hinder pest colonization by disrupting host signals through physical barriers, visual camouflage, and odor masking (Huss et al., 2022). Increasing the use of mechanical controls such as traps, barriers or physical pest removal, and cultural controls like intercropping may also help minimize insecticide use and associated environmental impacts in Japan.
3. Regulate and phase out hazardous insecticides. It is highly recommended that Japan tighten restrictions on high-risk compounds such as neonicotinoids, aligning with the European Union (EU)'s precautionary approach to protect pollinators and aquatic biota. In EU countries, which are also located in temperate region similar to Japan, neonicotinoids have been banned (EU, 2009) and

FIGURE 1
Herbicide-sprayed rice bunds in Japanese paddy fields. Comparable photo examples from Indonesia are presented in Amanda (2017) and Rosida et al. (2025).

EU drinking water standards are also lower than those implemented in Japan (EU, 2020; MHLW, 2003).

4. Promote organic insecticides. About 0.9% of total agricultural land in Indonesia was certified organic in 2014 (David and Ardiansyah, 2016), while Japan's organic farming covers approximately 0.5% of its total cultivated land as of 2018 (MAFF, 2020). Substituting conventional chemicals with organic insecticides and optimizing application timing may improve efficacy while minimizing ecological harm. Moreover, organic rice cultivation supports greater richness and abundance across multiple taxonomic groups, thereby enhancing biodiversity compared to conventional farming (Katayama et al., 2019).
5. Develop pest-resistant rice varieties. Temperate *japonica* type possesses fewer genes that confer resistance to major insect pests and insect-transmitted viral diseases compared with *indica* type (Hayashi et al., 2022). Though research has been ongoing, at present most rice cultivars grown in Japan tends to prioritize sensory qualities and climatic adaptability over pest resistance. In Indonesia, current research focuses on monitoring pest biotypes, rotating rice varieties, and diversifying resistance genes, with certain developed varieties also showing desirable agronomic characteristics such as high yield potential and good grain quality (Connor et al., 2024). Strengthening breeding programs to incorporate resistance traits in Japan, as practiced in Indonesia, may reduce pesticide reliance and delay resistance development in the country.
6. Foster international collaboration. Exchange of knowledge and expertise with countries implementing community-based IPM systems, such as Indonesia, may accelerate innovation and adoption of sustainable pest management practices in Japan.

On the other hand, Indonesia's early IPM implementation significantly reduced insecticide uses and enhanced ecological sustainability, yet recent trends indicate renewed chemical dependence, reflected in environmental contamination (Thorburn, 2015). Revitalizing a farmer-centred IPM framework, grounded in FFS principles and supported by policy integration and technological innovation, such as utilizing unmanned aerial vehicles or drones and artificial intelligence for precision spraying of insecticides like commonly used in Japan (Seo et al., 2023), is essential for reducing insecticide reliance and mitigating agrochemical pollution in rice ecosystems in Indonesia. It is also recommended to strengthen the regulations on insecticide use and thresholds because banned insecticides were still detected in the environment.

In addition to those recommended for each country, the implementation of the integrated rice–fish farming system, where fish naturally suppress insect pests by preying on them, may provide sustainable rice cultivation in both Japan and Indonesia. Research has shown that such systems can lower herbivorous insect populations by 24%, increase the abundance of invertebrate predators by 19.5%, and reduce pesticide use by 23.4% in China (Wan et al., 2019). In Japan, this traditional method originated in the early 1840s and spread widely during World War II (Koseki, 2014; Tsuruta and Iguchi, 2018). However, it declined sharply after the war with the growing use of chemical insecticides and the rise of specialized carp farming (Koseki, 2014). Today, only a few regions in Japan continue to practice it (Koseki, 2014). Meanwhile, known as 'mina padi' in Indonesia, this rice-fish farming practice began in West Java during the ninth century (Fyka et al., 2024) and has been further advanced since the 1970s with assistance from the Ministry of Marine Affairs and Fisheries and the Ministry of Agriculture (KKP, 2018). Nevertheless, its adoption remains limited, with only about 1.76% of the country's rice fields currently employing this method (KKP, 2018).

Another advantageous yet currently unutilized co-culture practice in Japan and Indonesia involves growing crops alongside edible fungi. The fungi can offer supplementary refuges for natural enemies and, to some extent, contribute additional predators that help control herbivorous pests in crops such as rice (Wan et al., 2024).

Furthermore, broader adoption of semiochemical-based management, which uses behavior-altering compounds to influence insect activity, may contribute to more sustainable rice cultivation. These approaches, especially pheromone-based techniques, are present in both Japan's and Indonesia's IPM. However, in Japan, their utilization is primarily concentrated in pest monitoring rather than large–scale replacement of insecticides (Yasuda and Higuchi, 2012), whereas in Indonesia, they are typically applied to specific crops, with emerging adoption in rice cultivation (Hasibuan, 2020). Allelochemicals like kairomones are used in palm oil plantation in Indonesia (Lingga et al., 2023), while information on other types such as allomones, synomones, and apneumones are scarce in both countries. Application of SPLAT (Specialized Pheromone and Lure Application Technology) to control the release of semiochemical formulation is also encouraged in Japan and Indonesia.

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