Rice–Aquatic Species Integration System (RASp)

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To ensure the sustainability of rice production and uplift the livelihoods of rice growers, agricultural diversification becomes imperative. By diversifying agricultural practices, farmers can strike a balance between rice cultivation and other crops, mitigating the environmental impacts of excessive input usage. Implementing innovative techniques, such as integrating rice with aquatic species (RASp), can optimize resource utilization and reduce reliance on vast amounts of water and synthetic inputs. Rice–aquatic species integration is a form of intensification where rice (R) remains the primary crop while aquatic species (ASp) become secondary products. This integration empowers efficient water use, offering a solution for sustainable food production. RASp presents an innovative and holistic farming system that harnesses the ecological synergies between rice and aquatic species to optimize resource utilization, enhance productivity, and mitigate environmental impacts.

rice–aquatic species integration alternate con-current productivity

1. Species, Feed, and Productivity (Profitability)

The traditional RASp includes rice-prawn/shrimp, snail, rice-tilapia, rice–carp, rice–crayfish, and rice–crab [1]. In China, *P. sinensis* is commonly reared in rice fields because of its high monetary value and its ability to produce high yields of rice and turtle without adversely affecting the quality of the water or soil compared to turtle monoculture [2]. However, *C. carpio*, *C.auratus*, and *O. niloticus* are the primary species stocked in rice fields in China [3][4]. *B. gonionotus* is frequently stored in polyculture with rice in paddy fields in southern Asia (India and Bangladesh) and southeast (Indonesia, Thailand, Malaysia, and Vietnam) Asia, while *O. niloticus* is the primary species in Ghana [3]. In Italy, *C. carpio*, *C. auratus*, and *Tinca tinca* are the most commonly distributed species. *Prochilodus argentes*, *Leporimus elongatus*, *Pimelodus clarias*, *C. carpio*, and *T. rendalli* are the most common species in both semi-intensive and intensive RASp integration in South America and the Caribbean. The most prevalent fish species in East & South East Hungary, India, and Indonesia, are common carp (*C. Caprio*). *C. carpio*, *Ictiobus cyprinellus*, and *Ictalurus punctatus* are the most common species in the United States (US). However, *C. carpio*, *B. gonionotus,* and *O. niloticus* are the main stocked species in rice fields in Cambodia, Laos, and Bangladesh, while *L. rohita* and *B. gonionotus* are the common species in Myanmar [4].

In India, the Indian Organic Aquaculture Project includes rotational cropping of organic rice and giant river prawns [2]. In south-western Vietnam, prawn farming dominates the Mekong delta, but other forms of commercial aquaculture, such as crab and mollusk farming, are also present in coastal areas, while freshwater fish farming in the inner section of the delta. In Myanmar, shrimp are produced in saline zones through alternating rice–aquatic species (RASp) integration, whereas little rice–aquatic species integration occurs in areas with fresh and brackish water [4][5]. The Macrobrachium species, Penaeus monodon, and other species, for instance, brackish water shrimps, are fish species that grow well in rice fields [1]. Tilapias can acclimate to changes in water levels and temperatures in rice fields to reduce the risks of ecological change, and they can also be cultivated in coastal brackish ponds [5][6][7][8][9]. In Bangladesh, tilapia can be grown as a variety of crops in systems with brackish water [5], while prawn and shrimp farming in rice fields are seen as an important component of the green economy and a technological policy for the integrated management of land, water, and aquatic species resources [10]. *C. chanos*, *Mugil* spp., and *Penaeus* spp. were utilized in brackish water. Other forms of integration include introducing livestock such as ducks (in Indonesia), Azolla (in China), chicken (in China), and pigs into rice–aquatic species in China, Indonesia, and India [11][12].

Fish in the RASp field consume rice weeds, and insect pests, while prawns primarily consume algae, insect larvae, and worms. In China, supplementary feed for the fish may consist of wheat bran, wheat flour, oilseed cakes (rapeseed, peanuts, soybeans, for instance), grasses, and green fodder, and in Malawi, maize bran and napier grass [13]. Li et al. [14] have suggested that the best way to achieve high-quality and high-yielding rice is to combine *indica* rice with fish that receive both organic and inorganic fertilizers. This method has proven most effective in humid regions with paddy soils containing low total nitrogen content (TN 1.5 g/kg), where an increase in rice yield is attributed to aboveground biomass, soil potassium (K^+), soil bulk density, water TN [15], rice planthopper, and soil redox potential (Eh). Applying the RASp integration system has dramatically reduced the quantities of chalky rice in the subtropical zone while increasing the proportions of brown rice, milled rice, and head rice. However, RASp did not have any discernible effects on other grain quality traits in the temperate zone [14].

Table 1 shows that the integration of RASp can lead to an increase in rice productivity ranging from 4.14 to 16.64% [1][2][3][16][17][18][19][20][21][22][23][24][25][26][27][28][29][30][31][32][33][34][35][36][37].

Table 1. Productivity of crops in rice–aquatic species culture among different countries in relation to rice monoculture.

Productivity (kg/ha/Season)			Fish Species	Reference	
Rice Mono-	**Fish**	**Rice**			
Bangladesh	4702	259	5261	*C. carpio*, *B. gonionotus*, *O. niloticus*	[17]
	4188	485	4736		[18]
	-	1453	2257	*Prawn & fish*	[19]
	-	827	2352		[20]
	-	1080	3800–5000	*B. gonionotus*, *O. niloticus*	[21][22]

Productivity (kg/ha/Season)			Fish	Reference	
Rice Mono-	**Fish**	**Rice**	**Species**		
Indonesia	-	300–890	6380–7780	*C. carpio*, *B. gonionotus*	[16][23]
China	7915–10,319	1900–2500	8300–12,000	*C. carpio*, *B. gonionotus*	[1][24]
		372	6290	*C. carpio var. color*	[25]
India	5560	1230	5800	*Rohu*, *Catla*, *Silver carp*, *Common carp*, & *Mrigal*	[26]
	-	1144	3300	*C. catla*, *C. carpio*, *C. mrigala*, *L. rohita*	[2]
	3362	980	3629	*C. catla*, *L. rohita*, *C. mrigala*, *C. carpio* & *M. rosenbergii*	[27]
	-	1300–2000	3000–3600	*B. gonionotus*, *C. catla*, *C. mrigala*	[28]
Ghana	-	201	4410	Nile tilapia (*O. niloticus*)	[3]
Vietnam	-	325–1218	2182	Mud Carp, Chub, Carp	[29]
	-	1024–2200	5700–6806	*C. carpio*, *B. gonionotus*, *O. niloticus*	[22][30] [31]
	-	326	4209		[32]
Thailand	-	173	363		[33]
	-	900–1100	-		[34]
	4700	300	3600	*O. niloticus*, *C. striata*, *C. carpio*, *B. gonionotus*, *C. cirrhosus*, *P. jullieni*, *C. batrachus*	[35]
Japan	4061–5319	345	4871–6381	*Carassius* complex, Goldfish	[36]
Nepal	3370	354	3670	Common carp (*C. carpio*)	[37]

us), while

s such as

ridge width or ditch width, the species cultured, regular food varieties (e.g., plankton, periphyton, and benthos), intensive or extensive farming, and the stage at which they were harvested. China had a fish yield of about 0.372–2.5 t/ha, followed by Vietnam (2.2 t/ha), India (1.1–2.0 t/ha), Thailand (0.175–1.1 t/ha), Bangladesh (0.259–1.45 t/ha), and Indonesia (0.89–1 t/ha), Ghana (0.2 t/ha), Japan (0.345 t/ha), and Nepal (0.354 t/ha) [38], as shown in **Table 1**. The combination of multiple species of fish tended to increase rice and fish productivity, particularly in India, where the combination of *B. gonionotus*, *C. catla*, and *C. mrigala* resulted in higher productivity compared to other species combinations.

Rice–fish farming in the coastal areas of Kerala (Pokkali fields) produced a fish yield of 229 kg ha^{-1} and a rice yield of 2.4–4.4 t ha^{-1} of salt-tolerant high-yield rice varieties [39]. In Vietnam's coastal areas, rice–fish farming yielded 2–

3 t of rice, 50 kg of shrimp, and 150–200 kg ha^{-1} of fish [40]. The gher system in Bangladesh consists of shrimp and fish culture with a yield of 280–450 kg ha^{-1}, depending on water exchange, followed by boro rice with a yield of 0.50–1.40 t ha^{-1}, or 3.2–7.7 t ha^{-1}, respectively. The system also yields 200–250 kg of shrimp and 150–175 kg of fish per hectare [41]. In rice–brackish water shrimp farming in five coastal provinces of the Mekong Delta, the average yield was 640 kg ha^{-1} of shrimp and 3.5–4.0 t ha^{-1} of rice [40].

These outcomes indicated that the yield components varied depending on the RASp model used, geographic distributions, the quantity and content of feed nutrients, types and amounts of organic and inorganic fertilizers used, and the density of aquatic organisms. Notably, rice yield significantly increased in the subtropical and tropical zones.

2. Water Quality, Soil, and Requirement for Water Levels

Depending on the water resources available, the integration of rice and fish systems can be achieved in various ways, such as irrigated, deepwater, rain-fed, and coastal systems [42]. Bashir et al. [43] suggest that the ideal conditions for RASp cultivation are a pH range of 6.5–9, 10 ppm CO_2, 5–7.5 DO (dissolved oxygen), 30–90 cm water level, 25–30 cm water transparency, and a temperature of 25–30 °C. RASp integration enhances water quality and abundant microorganisms, leading to improved performance, quality, and growth of tilapia muscle [44]. In addition, the levels of TN, ammonia-N, and TP in the water of catfish and shrimp ponds were substantially lowered by RASp [45]. Although rice cultivation in the catfish and shrimp ponds reduced respiration rates in the water and sediment, the respiration rates of the fish and shrimp remained unaffected [45]. The integration system improves the fertility of the soil and reinforces sustainable crop production [24][46]. Feng et al. [47] reported a 70–79% reduction in nutrient concentration in water samples in the co-culture compared to fish-monoculture, indicating that integrating aquatic species in rice fields can lessen environmental pollution. However, Li et al. [45] distinguish nine herbicides in 68 RASp and 30 sediment samples in the RASp integration in six provinces of China, posing ecological threats to the daphnia, fish, and algae.

The water depth required for successfully integrating the RASp system varies depending on different factors. Traditionally, rice monoculture employs shallow water, whereas RASp integration requires deeper water. In tropical conditions, continuous flooding of 2.5 to 7.5 cm of water is believed to provide an ideal environment for rice growth [48][49]. However, when rice fields are used for fish farming, deeper water is required. A deeper section of rice fields, called a fish refuge, is preferred by farmers for successful fish growth, with the ideal water depth for fish being 65–70 cm [50]. In Northeast India, the water level ranged from 1–3 cm in April, 10 cm from April to May, 51 cm on 15 August, and 24 cm at the time of fish harvesting in November [51]. In Bangladesh, prawn and small fish cultivation were maintained at water levels of around 30–40 cm in rice fields and 100 cm in ditches [52], while a water depth of 21 cm was needed for fish culture in rice fields [53]. In China and Bangladesh, the RASp integration was used at a depth of 20 cm [54][55], while in Vietnam, an average water level of 27 cm was observed in RASp integration [32]. In Thailand, the water level in RASp fields ranged from 15 to 35 cm throughout the rice growing season [35]. Hence, regional practices may differ slightly based on various factors.

In the coastal regions of Bangladesh, rice yield was not significantly affected by the depth of water (50 cm or 70 cm), while a higher yield of fish and shrimp was observed at the deeper depth of 70 cm. On the eastern coast of India, two water depths were identified: (1) a diversified farming system based on rice–fish integration for rainfed lowland (up to 50 cm water depth), and (2) a multitier farming system based on “rice–fish-horticulture-livestock” for deepwater (50–100 cm water depth) conditions. Sinhababu and Mahata [56] reported on the amount of rainwater harvested and its use in rice–fish diversified farming systems in rainfed lowlands in India. The 1300 m^2 pond refuge harvested 1820 m^3 of water, corresponding to an average water depth of 140 cm. After five years of on-farm rice–fish farming in coastal saline areas, Sinhababu et al. [57] observed a 50% reduction in water salinity in fish refuge ponds.

A major obstacle to the widespread adoption of the RASp integration system is the lack of access to sufficient water [17][49]. Insufficient water, drought, and irregular rainfall can adversely affect fish growth in rice fields. In shallow water, fish experience increased stress, which can negatively impact their survival, growth, and reproduction [58]. Low water levels have a significant impact on the total fish biomass produced in rice fields [59]. Therefore, implementing the RASp integration system is difficult when the water supply is limited.

On the other hand, flooding or excessive water is one of the primary concerns that the RASp integration system has. When rice ecosystems flood, fish may escape, and wild, predatory fish may enter, leading to lower yields due to predation and disease transmission. The water quality in rice fields is also affected by floods as land-based pollutants contaminate it, hindering fish growth and production. The financial limitations faced by small-scale farmers in developing nations prevent them from constructing sufficient dikes in their rice fields, leaving them at risk of flooding [50]. The height of typical dams is about 25–30 cm, and the same width [50], and it’s important to note that financial constraints are the main reason why these farmers cannot build dikes to the proper height and width. Rice fields with low and narrow dikes are at a higher risk of flooding, particularly for small-scale farmers in developing countries who cannot afford to build higher dikes [50]. Furthermore, sluice gates, which could help manage water levels efficiently, are often absent in rice fields. As rice is the primary crop in the RASp integration system, fish farming must adapt to the water availability and needs for rice production. To prevent fish from escaping or fleeing during floods, stronger dikes with fencing and netting can be constructed around rice fields [18].

3. Land Use Efficiency (LUE), Labor Use Efficiency (LBUE), and Water Use Efficiency (WUE)

In a study conducted by Dwiyana and Mendoza [16], it was found that rice–aquatic species (RASp) systems increased LUE by 1.74 times compared to rice monoculture. Additionally, the rotational fish culture (ROTF) system had an even higher LUE of 2.58 times than rice monoculture. However, rice monoculture was found to have a higher LBUE (USD 3.07 per man per day) than rice–aquatic species integration (USD 2.69 per man per day), according to the same study [16]. On the other hand, the LBUE achieved with ROTF integration was higher (USD 4.16 per man per day during the rainy season and USD 4.74 during the dry season) than that of rice monoculture. Among various rice–aquatic species systems, fish yield was found to be the highest. In Karnataka, India, the integrated RASp system was discovered to generate an additional 41.4% of jobs and also had a higher LUE than rice monoculture [60].

The concurrent cultivation of RASp in China requires approximately 26% more water than rice monoculture. Therefore, these models are not recommended for use in regions with limited or insufficient water supplies [61]. In the Philippines, the trench refuge and pond refuge regimes have been found to increase water requirements by approximately 23.3% and 26.3%, respectively, compared to rice monoculture [62]. According to **Table 2**, which presents data from various sources [12][18][63][64][65][66][67][68][69], the water use efficiency (WUE) for integrated fish in rice fields is reported to be 1.21 kg/m^3, which is at least 10% higher than the WUE for rice monoculture (0.85–1.60 kg/m^3).

Table 2. Comparison of rice and fish WUE (water use efficiency) values under various farming systems (FS).

Farming	Crop	Type of Study	WUE (Kg/m^3)	Reference
Agriculture (river water)	Rice	Crop production & land use [a]	0.74	[63][64]
		Experimental [a]	0.85–1.6	[65][66]
		Review [a]	1.09	[67]
Aquaculture	Fish	Assessment [a]	0.21–0.37	[68]
		Review [a]	0.36	[69]
		Experimental [a]	0.207	[12]
Integrated	Rice–aquatic species	Assessment [b]	1.21	[18]
	Pig–rice–catfish	Experimental [b]	4.31	[12]

Note(s): [a]: WUE calculates by dividing the yield by the amount of water consumed. [b]: The WUE is calculated in integrated systems by dividing the yield (rice + fish + any other species) by the total amount of water consumed by all participating enterprises.

The taller rice plants provide shade to fish during the hot season, reducing thermal stress and potentially decreasing water evaporation [70][71]. Moreover, the integration of pig–rice–aquatic species increases WUE by approximately 39% compared to rice monoculture and 28% compared to rice–aquatic species. This suggests that incorporating more enterprises into paddy fields results in higher WUE values.

No recent studies have been conducted to measure the water use efficiency (WUE), land use efficiency (LUE), and labor use efficiency (LBUE) of integrated rice and fish cultivation. Therefore, it is recommended that more recent research be conducted to assess these efficiency measures.

4. Greenhouse Gas (GHG)

Cultivation of fish in rice fields has demonstrated a significant reduction in methane emissions (by about 14.8–22.1%) and nitrous oxide (N_2O) emissions (by about 9%), despite rice monoculture increases the emissions of greenhouse gas (methane (12%) and nitrous oxide) by 2.5% from the total GHG. This is due to water mixing at different levels by the movement of fish species and livestock, which boosts the DO level in the field's standing water [72][73][74][75].

On the contrary, co-cultivation systems have been shown by several studies to result in a 26% increase in CH_4 emissions compared to monoculture systems [72][76][77][78]. However, the inclusion of fish, crabs, and crayfish in RASp (rice–fish, rice–crab, and rice–crayfish) significantly lessens N_2O emissions [78][79]. A rice–crab integration method minimizes seasonal N_2O emissions by 19.7–28% [78]. Additionally, the rice-cum-crayfish model reduced CH_4 emissions by 18.1–19.6% but increased N_2O emissions by 16.8–21.0% compared to rice monoculture model [80]. Co-culture RASp systems can reduce N loss from NH_3 volatilization and nitrate leaching while also promoting nitrogen use efficiency (NUE) through a reduction in N fertilizer applications [79]. Feng et al. [81] found that adding phosphorus to the RASp had no effect on CH_4 emission while adding K significantly increased CH_4 emission from the RASp by 18.4%. Combining P and K increased CH_4 emission from the RASp six-fold, with no effect on N_2O emission. In Germany, where the average temperature is 25 °C, the rice–carp model released the most methane, with an average of 13.6 mg m^{-2} h^{-1}, followed by the rice–carp/tilapia model, which released 12.1 mg m^{-2} h^{-1} on average, and the rice monoculture model, which released 10.7 mg m^{-2} h^{-1} on average [58]. Methane production is often higher in rice paddies with higher temperatures due to the growth of methanogens [82][83]. Yu et al. [15] estimated that CH_4 emission increases with temperature, precipitation, soil DOC (dissolved organic carbon), soil MBC (microbial biomass carbon), and soil dehydrogenase activity, while it (CH_4 emission) decreases with soil Eh, soil nitrate, soil ammonia, soil urease activity, water pH, and aboveground biomass. N_2O emission depends on soil SOC (soil organic carbon), soil MBC, soil Eh (redox potential), soil nitrate, soil ammonia, soil urease activity, soil dehydrogenase activity, and water DO.

Several studies have shown that co-culture systems can significantly reduce the global warming potential (GWP) of rice production. For example, in southern China, the GWP of rice-Gibel carp integration was 4611–4754 kg CO_2 ha^{-1} lower than that of rice monoculture (5391–5977 kg CO_2 ha^{-1}) [84]. Similarly, in China's Jianghan District, rice–crayfish integration had a GWP of 3847–7205 kg CO_2 ha^{-1}, lower than the rice monoculture value of 5828–8478 kg CO_2 ha^{-1} [79]. Xu et al. [85] reported a reduction in GWP of 11.1–21.1% with the rice–crayfish integration model compared to rice monoculture. However, in the northeastern part of China, rice–crab integration (both juvenile and megalopa) had a GWP between 9293 and 9811 kg CO_2 ha^{-1} higher than rice monoculture (7275 kg CO_2 ha^{-1}) [77]. Previous studies conducted in East Asia have consistently found that co-culture systems effectively reduce CH_4 emissions and global warming potential (GWP) from rice paddies [79][82]. However, research conducted in South Asia showed that the RASp model resulted in a significant increase in CH_4 emissions ranging from 26% to 112% and GWP by 11–22% [58][72][77][83]. This difference could be attributed to variations in mean annual temperature and precipitation across different geographic locations.

The results indicate that CH_4 and N_2O emissions vary based on factors such as the type of aquatic species used in the co-culture system, fertilizer usage, mean annual temperature, and precipitation levels. Further research is needed to better understand the overall production and emission of CH_4 and N_2O, particularly under conditions of changing water levels, feed input, species and fertilizer types, RASp stocking density, and varying temperature and precipitation.

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