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RESEARCH ARTICLE

Three-tier farming in rice agroecosystem of Apatani Plateau in Arunachal Pradesh, India

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Abstract

The Ziro Valley of Arunachal Pradesh hosts a distinctive high-altitude integrated paddy–fish–millet farming system developed by the Apatani tribe of Northeast India. In contrast to the dominant lowland rice–fish systems of Southeast Asia, this agroecosystem operates at elevations of ~1,500–1,700 m under temperate climatic conditions. Wet rice is cultivated in terraced plots while Common Carp (*Cyprinus carpio*) are reared in the flooded fields, and finger millet (*Eleusine coracana*) is simultaneously grown along the bunds. Synergistic interactions among rice, fish and millet enhance nutrient cycling, reduce pests and weeds, and maintain productivity without external agrochemical inputs. This paper documents the structural features, operational stages, ecological functions of the system based on field observations, secondary literature and ethnographic sources and also highlights some recent inputs that have been incorporated through adoptive endeavours for better output towards further refinement of the system. The findings underscore the role of traditional ecological knowledge in sustaining a resilient and resource-efficient mountain agroecosystem with relevance for contemporary sustainability, climate adaptation and indigenous food security agenda.

Keywords: Paddy-fish-millet farming; Sustainability; Low-land terrace farming; Ziro; Arunachal Pradesh

1. Introduction

Integrated rice-fish farming is an ancient agricultural practice that integrates rice cultivation with fish farming in the same field. This symbiotic system enhances productivity, minimizes the need for chemical inputs, and fosters ecological balance. The activities of fish aerate the water, reduce weeds, control pests and release nutrient into water, while rice provides shade, substrates for growth of fish feed and seasonal fish shelter underneath canopy during rice growing seasons. This concurrent cultivation of paddy and fish, also known as rice-pisciculture, is considered as one of the most efficient and sustainable methods of land use and food production (Ahmed and Turchini, 2021).

Originating in China, this farming system is now practiced in many parts of the world, especially in Southeast Asia, where rice and fish are staple foods (Halwart, 1998). In India, it is traditionally practiced in several eastern regions, such as *Zabo* cultivation by the Chakhesang tribe in Nagaland, the *Pokkali* system in Kerala, and the *Bhasabandha* or *Bheri* system in the Sundarbans of West Bengal (Sathoria and Roy, 2022). Among these, the most notable is the 'paddy-cum-fish culture' which is practiced entirely as organic system by Apatani tribe of Arunachal Pradesh.

The Apatani, having a deep harmony with nature, their primary form of sedentary agriculture known as "paddy-cum-fish culture," is an ingenious integration of rice and fish farming within the same fields. This system not only sustains the livelihood of the community but also exemplifies a time-tested model of resource optimization and ecological balance (Wan et al., 2019; Sathoria and Roy, 2022; Yifan et al., 2023; Myo et al., 2024). Practically, the possession of limited geographical area becomes one of the key reasons for adopting such a farming strategy amongst Apatani settlers that enables them to make the efficient use of their essential resources. Moreover, the integration strategy being introduced by the early settlers in this land-locked mountain valley has successfully been passed down through generations. The practice of capturing fish from rice fields began in the valley when the stream fish such as, *Channa* spp. (*Tali ngiyi*), *Puntius* spp. (*Papi ngiyi*), Eels (*Tabu ngiyi*) *Schizothorax* spp (*Ngilyang ngiyi*) naturally entered the rice fields with flood water. These fish typically migrated from nearby rivers, pools, mountain streams into rice fields through irrigation channels and rainwater during rice growing season and they grazed and grew concurrently with the rice plants. These occurrences of fishes in paddy fields of mountain valley led the Government of Arunachal Pradesh to formally launch the scheme of 'paddy-cum-fish' culture in the Apatani Valley during the 1960s keeping parity with first Indian Council of Agricultural research (ICAR) scheme of 1959 on this dimension (Kacha, 2016). As the dweller of higher altitude, Apatani people are very industrious and hardworking where men, women, and even children actively participate in agricultural activities and both men and women collaborate in tasks such as building bunds, harvesting paddy, maintaining community irrigation canals, and fencing the fields to protect crops from raids by Mithun (*Bos frontalis*) and cattle. Women primarily handle the transplantation of paddy saplings and weeding, contributing significantly to the smooth functioning of such agro-farming ventures.

The integrated rice-fish cultivation systems in Southeast Asia and the Apatani tribe's traditional practices in Arunachal Pradesh share notable similarities in their sustainable and symbiotic approaches. However, they differ significantly in

Table 1. Documented characteristics of the Apatani Paddy–Fish–Millet farming system in Ziro valley

Category	Documented Characteristics
Landscape Setting	Terraced paddy fields in an intermontane basin at ~1,500–1,700 m elevation; bunds defining individual plots; perennial hill streams supplying water.
Crop Components	Wetland rice (main crop), finger millet on bunds (secondary), occasional vegetables/perennials on margins.
Fish Component	Common Carp (*Cyprinus carpio*) and its other strains stocked in flooded paddies during growing season. Alternated with grass carp (*Ctenopharyngodon Idella*)
Soil & Fertility Management	Predominantly organic; use of livestock manure, decomposed rice straw; no synthetic fertilizers observed.
Water Management	Gravity-fed irrigation from hill streams; multi-tier channels with inlets and outlets for each plot; regulated via bamboo/PVC pipes and earthen plugs.
Stocking & Crop Calendar	Rice transplanted first, carp stocked after establishment; millet sown on bunds concurrently; fish and millet harvested first, followed by rice.
Feeding Practices	Mixed feeding: natural resources (periphyton, detritus) + kitchen waste and rice bran; occasionally fish feed provided by the department (Fisheries)
Field Operations	Manual transplantation, weeding, bund maintenance, irrigation control; use of wooden tools and bamboo implements.
Output Diversity	Rice (staple), fish (protein and cash), millet; multi-output system increases subsistence and market resilience.
Provisioning Functions	Provides cereals, animal protein, and supplementary grain; supports household food security with local market surplus.
Regulating Functions	Reduced pest load due to fish predation; erosion control via millet roots; nutrient redistribution through water flow; weed suppression via flooding.
Supporting Functions	Soil fertility through organic matter recycling; aquatic primary productivity (periphyton/invertebrates); genetic resource preservation (seed systems).
Cultural and social dimensions	Traditional ecological knowledge (TEK) guides irrigation timing and cultivation; communal water governance; intergenerational knowledge transfer through elders and youth.
Labour organization	Household-based labour with gendered task division; women plays the major role; youth (both men and women) participate in harvest
Market Orientation	Household consumption plus local market sale of surplus fish; limited commercialization.

perspective where the primary distinctions lie in the altitude at which these systems are practiced. Most rice-fish farming systems in Southeast Asia, including those in Vietnam, Indonesia, and Thailand, are located at low altitudes, typically below 300 meters (1,000 feet) above sea level (Nhan et al., 1997; Rothuis et al., 1998; Yassi et al., 2023). Further, the regions are characterized by warm, humid tropical climates, abundant monsoonal rainfall, and flat terrains, making them ideal for large-scale rice and fish cultivation (Huat and Tan 1980). In contrast, the Apatani tribe practices rice-fish farming in the Ziro Valley, situated at an altitude of approximately 1,500–1,700 meters (4,900–5,600 feet) above sea level. Being nestled in a temperate mountainous region, the valley experiences a cooler climate, which influences the growing season, crop varieties, and also selection fish species to be stocked. The steep terrain compels the use of terraced fields devised with traditional irrigation systems for ensuring precise water management. Each terrace is carefully levelled to distribute water uniformly, altering this practice more labour-intensive.

Further, distinction also lies in the cropping patterns of the system. In some Southeast Asian countries rice cultivation is rotationally followed with fish/shrimp farming i.e. alternate between cropping seasons (Preston and Clayton, 2003). On the contrary, the Apatani people are adopted to practice the concurrent cropping of rice and fish together i.e. as simultaneous crop along with kharif rice (Reena and Nani, 2014; Kacha 2016; Baruah and Singh, 2018). Additionally, the crop of finger millet, locally called *Sarse* (*Eleusine coracana*) is grown along the bunds of the terraces. This integration not only aids in soil conservation but also abets to prevent erosion during torrential rains and also resists pressure of waterlogging in to depth of paddy fields. This holistic approach ensures the efficient resource utilization from the rice agroecosystem within the available time and space. It is also noteworthy that the “integrated paddy-fish-millet farming” system is practiced without the use of machinery, technical intervention and inputs of agro-chemicals. This is decidedly refined system of valley cultivation, perfected over centuries and has led the scholars to regard the Apatani community as one of the specially advanced tribal societies in north eastern India.

While deeply rooted in traditional ecological knowledge (TEK), the system is not static. In recent decades, Apatani farmers have selectively incorporated adaptive inputs and refinements aimed at improving yield, labour efficiency and water management. This paper along with exploring the intricacies of the integrated paddy-fish-millet cultivation system of Apatani farmers, examining its farming design, grow out operations along with ecological dynamics and significance, also highlights some recent inputs that have been incorporated through adaptive endeavours for better output towards further refinement of the system. Thus, the paper accentuates traditional farming's role on the global discourse of sustainable agriculture and biodiversity conservation by documenting and analysing practices of the farmers as a whole.

2. Material and method

2.1. Study area

The study was conducted in the Ziro Valley, located in Lower Subansiri district of Arunachal Pradesh in Northeast India (27.59°N, 93.82°E). The valley lies at an elevation of approximately 1,500–1,700 meters above mean sea level and consists of an intermontane basin surrounded by forested hills. Ziro has a humid subtropical to temperate climate, with distinct monsoon precipitation from May to September and relatively dry winters. The valley is surrounded by hills and ranges in all directions, with the Kiiley River flowing from north to south through the valley. This river, along with its tributaries, provides ample water for rice cultivation in the region. Out of the total wet area of 715.7 hectares, approximately 592 hectares of wet fields are dedicated to rice-fish integrated culture and the area is surrounded by hills and mountains covered with vegetable gardens, pines, bamboos and other trees (Kacha, 2016). The soils of Ziro Valley are humid and range from black to reddish in colour, with loamy to sandy-loam textures. They are mildly acidic (pH 5.0–6.0) and contain high organic carbon with adequate phosphorus and potassium (Dollo et al., 2009), making them suitable for diverse crops. The indigenous Apatani tribe forms the dominant population of the valley and practices integrated wet rice cultivation, fish rearing and bund-based millet cultivation as part of a long-standing Traditional Ecological Knowledge (TEK) system (Tayo et al., 2017).

2.2. Data collection

Primary data for this study were collected through field observation and informal interviews conducted in four villages (*Hari, Bulla, Hong* and *Hija*) in Ziro Valley from year 2023 to 2025. Field observations included walkthrough surveys of agricultural terraces, irrigation channels, nursery plots and bunds, documenting cropping stages, water management and fish stocking practices. Informal, unstructured conversations were conducted with elders, farmers and youth engaged in agriculture and daily field activities. These interactions focused on cultivation sequences, water control, crop and fish management, input use and recent changes in practice. No personal or sensitive information was collected, and interactions were guided by respect for cultural norms, without invasive questioning or formal data extraction. Primary observations were complemented by an extensive review of secondary sources including relevant scientific papers, ethnographic accounts, agronomic studies, ecological assessments etc.

3. Result and discussion

3.1. Traditional 'paddy-fish-millet' farming practice of Apatani tribe

The 'paddy-fish -millet' cultivation system practiced by the Apatani tribe in Ziro Valley is a highly structured and sustainable agricultural method which utilizes a single piece of land for paddy cultivation, fish rearing within the flooded fields and simultaneously growing millets on the surrounding bunds (Figure 1). In the rice fields (locally known as *Aji*) paddy seedlings are transplanted into puddled field soil and companion crop of fish (*Cyprinus carpio*) fry are stocked into field water, while millet saplings or seeds (cultivar: finger millet *Eleusine coracana*) are sown on the field dykes or bunds that separate each plot. The steps and processes involved in this unique farming system are detailed below. Characteristics of the farming system is also documented in Table 1.

3.1.1. Field preparation

The steep slopes designated for cultivation are first converted into level terraces with raised bunds (*Agher*) to retain water. The bunds are fortified using local materials like clay, stones, wood and grasses to prevent erosion and water leakage. It is essential to ensure that the bunds are strong and durable, as fish are also reared alongside the paddy. It is then followed by canal preparation. Canals are dug out to a depth of 1.5 to 2 feet across the paddy fields, dividing the plot either perpendicularly or horizontally along the bunds. The number, depth, and length of these canals depend on the size of the plot. Eventually, all the smaller canals merge into a main canal, where an outlet point made of bamboo pipes is installed at the lowest point across the bund for complete draining out of the field water whenever required.

The canals provide shelter during harsh conditions or low water levels in paddy fields, while also serving as rearing spaces for fish. Simultaneously, the field is ploughed and leveled for rice cultivation. Unlike other communities, the Apatani traditionally do not use cattle, or any livestock or machinery for ploughing. Instead, they rely on manual labour using their legs and a locally made wooden tool called the *Sampya*. This equipment, loaded with soil and tied with a rope at one end, is pulled manually to level the field effectively.

3.1.2. Irrigation system

The Apatani have developed a sophisticated and sustainable irrigation and water supply system for paddy and fish cultivation, featuring an intricate network of feeder channels that ensure consistent water distribution to every rice plot across the plateau. The primary water sources include the *Kiiley* River, perennial streams, and natural springs originating from the surrounding hills of Ziro Valley, providing a consistent water supply throughout the year. During the monsoon season, rainfall replenishes these water sources, supporting the irrigation system further. Water from the streams is taped just before entering into the agricultural valley/cultivated fields, channeled and diverted towards a single canal to which each field is connected with bamboo pipelines or pinewood pipe (Dollo et al., 2009). Water flows from higher terraces to lower ones through carefully designed outlets or connecting ducts called *Hubu*.

For effective water management system paddy fields has two outlets and one inlet. One outlet (*Hubu*) is used to divert overflow of water, barricaded with split bamboo net to prevent the escape of fish from paddy field, while the other (*Siicho*) remains at the bottom in main canal, is meant for complete drainage of water during harvesting of fish and before harvesting of paddy to make the field dry for convenient movement of worker during harvesting time. The inlet of a lower terrace acts as the outlet of the higher one, creating a staircase flow pattern down the valley. Excess water from the fields is drained into the *Kiiley* river, which flows through the middle of the valley. The water level in the rice fields is maintained by adjusting the height of the *Hubu*. Typically, a 10 cm water level is maintained by setting the *Hubu* at the appropriate height. *Siicho* outlets are usually made from pinewood, which is durable and resists decay as it remains submerged in water. Meanwhile, *Hubu* outlets are often made from large bamboo, though these require periodic replacement. In recent times, bamboo pipelines are increasingly being replaced with plastic pipes due to low maintenance cost and better durability. Additionally, the irrigation channels carry runoff effluents formed from decomposed leaf litters that enrich the soil as natural input of manure and supporting farming practices. This integrated system reflects the Apatani's ingenuity and their commitment to preserving ecological balance while maximizing agricultural productivity.

3.1.3. Manuring of the field

The manuring of fields is a vital component of the Apatanis' sustainable agricultural practice. This process relies heavily on organic inputs and natural recycling methods, enriching the soil and enhancing the productivity of rice, fish, and millet. Manuring is typically carried out between November and January.

Organic materials such as poultry feces (*Paro Pai*), pig excreta, cow dung, rice husks (*Pinang*), by-products of local beer production (*Ooh Poi*), ashes from household firewood (*Mubu*), and burnt straw ashes (*Muyu*) are applied to the fields after the harvest. Additionally, crop residues, such as rice straw, are left in the fields to decompose naturally. The Apatani consider this to be the most effective method of manuring, as the decomposition process enriches the soil with essential nutrients, significantly improving its fertility. The fish cultivated in the fields contribute significantly to soil enrichment. Fish cultivated in the fields also play a significant role in soil enrichment. Fish excreta act as a natural fertilizer, contributing organic matter and nutrients to the water, which are readily absorbed by the rice plants. Manure is applied before and during the flooding of the fields to ensure even distribution. Additional applications may be made at critical growth stages of rice to boost yields.

3.1.4. Setting Nursery (Rice bed)

The rice bed or nursery (*Miding*) is prepared after the field is ready or simultaneously. These nurseries are well-protected to prevent the entry of stray animals. The size of the nursery bed typically ranges from 15 m^2 to 60 m^2, further divided into small compartments measuring approximately 4 x 1 m (length x breadth). This division allows excess water to drain through depressions between the compartments. A specific field, usually located near the household, is designated for the nursery and is kept filled with water throughout the year. Monthly weeding is carried out to maintain its condition. Various indigenous paddy varieties, locally known as *Mipya*, *Emho*, and *Pyaping*, are sown (*Andhi Lilo*) from mid-February to the first week of March after the nursery bed has been prepared.

Figure 1. Three-Tier Farming in Rice Agroecosystem of Apatani Plateau: **A.** Rice Bed/nursery, **B.** Millets grown on the bunds, **C**. canal for fish rearing, **D**. Bamboo barricade (prevents fish from escaping), **E**. Cemented bunds, **F**. connecting ducts (Hubu), **G & H**. Rice-fish coculture; harvesting of fish (common carp).

The nursery bed's moisture level is carefully regulated-neither too dry nor too wet during sowing and germination to ensure a high germination rate. Each rice variety is maintained separately in nursery bed in order to avoid the possible mix up of seedlings. These paddy seedlings (*Andhi*) take 70-80 days until they attain the height of about 15-20 cm, at which point they are transplanted into the paddy field. Among the varieties, *Mipya* ripens earlier, while *Emho* takes slightly longer due to its grain structure and growth habit.

The finger millet nursery (*Sarse Paap*) is raised in distant home gardens (*Yorlu*) or kitchen gardens (*Ballu*). It takes 80–90 days for the seedlings to grow to a height of 10–15 cm before being transplanted onto the paddy field bunds.

3.1.5. Transplantation of paddy sapling

Once the seedlings (*Andhi*) are mature, they are carefully uprooted from the nursery bed and transplanted into the main flooded terraces. The saplings are plucked from the nursery bed and bundled together using weeds, locally called *Mima* (*Juncus himalensis*). Transplantation of *Mipya* (an early ripening paddy variety) begins between April and the first week of May. The process is done manually by hand, planting one sapling at a time. A spacing of 10–15 cm is maintained between each plant in a row. In the subsequent row, the saplings are planted 10–15 cm apart in the gaps between the plants of the previous row, creating a staggered pattern. This process continues systematically until the entire plot is planted.

3.1.6. Introduction of fish

After the paddy plants are well established, fish fingerlings are released in the same field, usually in the month of May. Typically, common carp (*Cyprinus carpio*) and other native fish species are introduced into the flooded fields. Apatani grow all the strains of Common carp viz. Mirror carp (*Cyprinus carpiospecularis*), leather carp (*C. carpionudus*), Scale carp (*C. carpiocommunis*) (Tayo et al., 2017). This integrated system allows rice and fish to mutually benefit each other, enhancing productivity and sustainability. Fish excreta act as a natural fertilizer, providing essential nutrients like nitrogen, phosphorus, and potassium to the rice plants. The decomposition of leftover fish feed further enriches the soil, promoting healthier crop growth. Fish farming also aids in weed and pest control through the fish's feeding behavior. Fish help control the growth of algae, weeds, and insect larvae in the water, reducing competition for nutrients and protecting rice plants from pests. This reduces the need for manual weeding and pesticide application (Jyoti et al., 2020). Additionally, the movement of fish in the water aerates the submerged soil, improving oxygen availability to the rice plant roots and enhancing overall plant health (Cruz, 1994). Conversely, the paddy plants provide shade to the water, maintaining cooler temperatures and creating a suitable habitat for fish. Reduced sunlight exposure helps control water temperature, while the aquatic ecosystem in the rice field supports natural fish feed, such as plankton, insects, and organic debris. Common carp in the rice fields of the Apatani Plateau primarily feed on periphyton colonizing the underwater parts of rice stems. Decaying rice roots and leaves also contribute to the fish's diet. Moreover, the growth of paddy plants offers shelter to the fish, protecting them from birds and other predators.

3.1.7. Integration of finger millet

Transplantation of millet saplings is carried out in May, following the transplantation of paddy, once the millet saplings reach a height of 10–15 cm. Finger millets are planted along the bunds, which help conserve soil and prevent erosion. The roots of the millet bind the soil, reducing nutrient loss during heavy rains, thus preventing soil from washing away and maintaining the structural integrity needed for fish rearing. The millet saplings are sown using a traditional wooden spike called *Damu*. Holes are made in the bunds for planting the millet in a similar pattern as paddy, with one hole per sapling. Each hole is then covered with soil using fingers.

3.1.8. Weeding

The Apatani people are known for keeping their fields exceptionally clean. There is a saying that their fields are cleaner than their households. Weeding (*Tami Hodu*) is done at least three times until the paddy reaches the milking stage. The first weeding takes place in February, then in the month of May after the transplantation of the paddy. If the early saplings do not survive, re-transplantation is carried out. Afterward, weeding is performed once every two months, from June to August, until the paddy reaches the milking stage. The weeds are gathered into small piles and pushed to the bottom of the paddy field with feet, as the field is moist and loose due to the presence of water. In this way, the weeds decompose beneath the field, enriching the soil with nutrients.

3.1.9. Harvesting

Fish released in April or May are the first to be harvested in July or August. After draining the water from the fields, the fish are caught manually using hands or traditional baskets. After keeping some for home consumption, the rest are sold in the market. Finger millet is harvested in August or by September, yielding an additional crop alongside rice. The millet is cut at the neck using a sickle. It is used to make wine and serves as a food source. Millet flour is eaten by mixing it with hot water, a traditional dish, or used in the preparation of various local sweet dishes.

Paddy is harvested from the end of September until the third week of October. Few days prior to harvesting, the water in the field is completely drained by opening the bottom outlet pipe (*Siicho*). The paddy harvest is one of the most interesting parts of the entire cultivation process, with men and children also participating. Women cut the paddy with a sickle at the middle of the stalk, gathering a handful of cut paddy, which she hands over to a man standing behind her. The man carries a basket made of bamboo (*Yagii*), with a wooden plate hanging inside. He thrashes the paddy in the basket by hitting the wooden plate, and the grains are collected in the basket. When the grains fill half the basket, it is emptied into a common collection center on a large mat. In the evening, the collected grains are transferred to a granary, locally called "*Nesu*," which is built 50 to 100 meters away from the dwelling to minimize the risk of fire.

3.1.10. Post-harvest activities

After harvest, the thrashed paddy straw is either left in the field or collected and used as fodder for livestock or as a substrate for mushroom cultivation. In the past, it was also used for thatching roofs. The paddy stalks that remain in the field, along with the straw, are left to decompose. This process is considered the best way to incorporate nutrients into the soil. Some people burn them in the field, which kills insects and maggots, and the ash provides nutrients to the soil. However, this method is not widely preferred.

Later, during November and December, canals are prepared for the next round of cultivation. The water is completely drained until the plot is dry and cracked. This is done to prevent pest attacks on the paddy saplings. It has been observed that if the paddy field remains wet after harvesting until the next transplanting season, maggots develop on the roots of newly transplanted saplings, causing them to die. The maggots attract crows, which in turn pull out the paddy saplings to eat them. In January and February, bunds are repaired to ensure they can withstand the pressure of water during the peak of the rainy season.

3.1.11. Modernization of traditional agricultural practices

Although the Apatani are self-sufficient through their traditional agriculture, over the generations, they have adopted a few incremental changes based on traditional ecological knowledge, while maintaining their cultural practices. These modern adaptations are required to address few challenges such as population, increased demand for food production, climate change, economic stability, resource management, technological advancements etc. thereby improving the sustainability, efficiency, and productivity of their agricultural practices.

Few adaptations that are practiced in recent times are discussed below:

i. In the traditional agricultural system of the Apatani, the outlet pipe (*Hubu*) that is used to divert the overflow of water from fields, were traditionally made from large bamboo sections, which were cut and shaped to channel excess water away from the fields. However, in recent times, these bamboo pipes are increasingly being replaced with plastic pipes. The main reason for this shift is that plastic pipes require significantly lower maintenance compared to bamboo pipes. Bamboo, while durable, is prone to wear and tear over time due to factors like rot, insect damage, and weather conditions. As a result, the bamboo pipes need to be periodically replaced or repaired, which can be time-consuming and costly.

ii. In recent years there have been changes in bund construction as well. The bunds are built very strong as farmers practice wet rice cultivation alongside fish rearing. To reinforce the bunds, finger millets are grown along their edges to prevent soil erosion and slogging during torrential monsoon rains. Traditionally, bunds are made using clay, stones, and other locally available materials. The lower portions of the side walls are often covered with pine bark (locally called *Bakoli*) to protect the bunds. Pine bark is valued for its durability and resistance to weather, making it a sustainable choice. However, with changing climatic conditions, prolonged and intense monsoon rains often lead to flooding, sometimes causing even the strongest bunds to erode or collapse. This results in the escape of fish and damage to paddy crops. This remains as one of the most challenging aspects for the farmers. To address this issue, some farmers have started using cement to construct the side walls of bunds. Cemented walls are stronger, more durable, and can withstand heavy rains. Cementing also helps prevent encroachment from neighboring fields, as it creates a clear and permanent boundary. However, while cemented bunds are effective, the higher cost limits their adoption to wealthier farmers, leaving traditional methods as the only option for others.

iii. Alternating with culture of grass carp (*Ctenopharyngodon idella*): Before the harvest, the field is completely drained and kept dry until the next transplantation. Recently, some farmers have adopted a different method. After the harvest, typically in November, the field is filled with water, and grass carp fingerlings are introduced. Grass carp (*Ctenopharyngodon idella*) are herbivorous fish that feed on aquatic weeds, helping to naturally manage weed growth. By feeding on the weeds, the grass carp minimize the labor-intensive process of manual weeding during February. Farmers gain an additional harvest in the form of fish, supplementing their income and diversifying farm outputs. This method promotes environmentally friendly practices by utilizing fish as biological weed controllers, reducing the need for herbicides or excessive labor. Although this method is innovative and has potential benefits, it is still in its early stages of adoption and is practiced by only a small number of farmers in the Ziro Valley. This limited uptake may be due to a lack of awareness, resources, or expertise in fish farming.

iv. When finger millet is not grown along the bunds, farmers often utilize these spaces to grow alternative crops, such as Soybean (Local name: Amm Peruñ; *Glycine max*), maize (*Zea mays*), and bitter eggplant (Local name: Byaako; *Solanum aethiopicum*). These bunds, which separate the fields and retain water, provide fertile and well-drained soil suitable for growing vegetables and other crops. It thus ensures that no part of their agricultural land remains idle, maximizing the productivity of their fields. Growing vegetables and other crops alongside paddy and millet diversifies farm output, allowing farmers to meet both household consumption needs and market demands.

v. Paddy cultivation combined with fish rearing is becoming increasingly popular among farmers as a subsidiary occupation due to the growing demand for fish in the local market. This integrated practice not only enhances farm productivity but also provides an additional source of income, making it a sustainable and economically beneficial approach to agriculture. As a result, some progressive farmers rear fingerlings in two batches: the first batch is released in January or February and harvested in April or May, before the transplantation of paddy saplings. The second batch is released in April or May, about one week after the transplantation of paddy saplings, and harvested in July or August. This method allows two batches of fish to be reared and harvested in a single year from the same paddy field. It has been observed that fish released in April or May grow faster compared to those released earlier in January or February (Tayo et al., 2017).

vi. Use of machines: There have been reports of the gradual adoption of machines, such as power tillers, for ploughing fields. Traditionally, ploughing and leveling are done manually, a process that requires significant time and effort. To reduce this labor, some farmers have started using power tillers. However, due to the narrow bunds in most fields, these machines are typically used only in fields located near roads or where the bunds are sufficiently wide as it becomes difficult to maneuver machines. Power tillers are either personally owned or rented, but not everyone can afford to purchase one or pay the rental charges, limiting their use to a small segment of farmers. Despite these advancements, many farmers still prefer the traditional manual method due to economic constraints and the practical challenges of using machines in certain field conditions (terrain).

These are some of the major modern adaptations incorporated into the traditional farming system of the Apatani people, allowing them to maintain their cultural practices while embracing innovation. This approach helps achieve a delicate balance between tradition, modernization, and sustainability. It also highlights the Apatani people's ability to adapt while staying rooted in their traditions, promoting sustainability in their farming practices.

4. Conclusion

The Apatani traditional farming system reflects a harmonious blend of ecological knowledge, cultural heritage, and environmental stewardship. Their reliance on organic manuring showcases their deep understanding of sustainable agriculture. The practices not only maintain soil health but also support the ecosystem, making this traditional system a model for sustainable farming worldwide. The irrigation system is also a fine example of sustainable water management. It maximizes the use of natural resources, minimizes wastage, and supports biodiversity. This traditional method demonstrates a harmonious relationship between agriculture, aquaculture, and the environment, making it a vital practice for food security and conservation in Ziro Valley. Documenting such systems expands understanding of agroecological pathways beyond industrial intensification, highlighting the role of indigenous innovations in sustainable development. By practicing this integrated method, the farmers of Ziro Valley enhance the sustainability and productivity of their agricultural system while making the most of their available resources. However, despite its effectiveness in fostering self-sufficiency, modern challenges such as population growth, increased food demand, climate change, and economic pressures have necessitated incremental adaptations. The incorporation of contemporary practices, such as fish-cum-paddy farming, the use of plastic pipes, mechanization, and the strengthening of bunds, demonstrates the Apatani people's resilience and willingness to innovate without losing their cultural identity. These changes are critical in ensuring that their agricultural practices remain sustainable, productive, and efficient in the face of modern-day challenges. Traditional agricultural systems should be improved gradually, building upon traditional ecological knowledge, rather than undergoing abrupt transformations, as drastic changes may not be well-received by the local communities. There are several opportunities to enhance this system to enable farmers to achieve higher returns, such as:

***Improved Awareness and Training**:* Conducting regular workshops and training programs to educate farmers about sustainable modern techniques, such as advanced fish farming, organic fertilizers, and integrated pest management, can help enhance productivity while maintaining ecological balance.

***Affordable Mechanization**:* Making agricultural machinery like power tillers more affordable or accessible through government subsidies or cooperative ownership models can help more farmers adopt these labor-saving tools. Adaptations for narrow bunds and rugged terrain could also increase usability.

***Climate-resilient practices**:* Research and development of bund materials and designs that can better withstand extreme monsoon rains are crucial. Expanding the use of durable, cost-effective alternatives to cement, such as eco-friendly composites, could be explored.

***Diversification of crops**:* Expanding crop diversity by introducing high-value crops, medicinal plants, or horticultural species that complement traditional farming systems can provide additional income sources and promote food security.

***Market development and accessibility**:* Strengthening local markets and connecting farmers to larger markets for fish, vegetables, and value-added products like millet wine or organic produce can improve their economic stability.

***Research and innovation**:* Collaborative efforts with agricultural research institutes to study the Apatani farming system and its unique challenges can lead to the development of tailored solutions. For instance, exploring native plant species that can further prevent soil erosion or pests could prove beneficial.

By embracing these future prospects while preserving their cultural identity, the Apatani people can continue to lead as a model of sustainable and innovative traditional farming systems. This balanced approach ensures the preservation of their heritage while securing a productive and resilient agricultural future. Future work should assess productivity metrics, ecosystem service valuation, and market integration to inform policy and conservation strategies.

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Author's contribution

Hage Yakang: Conceptualization, Methodology, Writing – original draft. Oyi Dai Nimasow: Writing – review & editing. D.N. Das: Writing – review & editing, Supervision

Conflict of interests

Authors declare no conflict of interest

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