Organic Farming
https://www.acadlore.com/journals/OF

Community-Based Waste Mapping in the Traditional Subak Irrigation Systems: Evidence from Penebel District in Bali, Indonesia

I Ketut Sardiana[1*], Putu Perdana Kusuma Wiguna[1],
Anak Agung Ayu Wulandira Sawitri Djelantik[2], Ni Made Ari Kusuma Dewi[3]

[1] Study Program of Agroecotechnology, Faculty of Agriculture, Udayana University, 80232 Denpasar, Indonesia
[2] Study Program of Agribusiness, Faculty of Agriculture, Udayana University, 80232 Denpasar, Indonesia
[3] Study Program of Animal Husbandry, Faculty of Animal Husbandry, Udayana University, 80232 Denpasar, Indonesia

[*] Correspondence: I Ketut Sardiana (ketutsardiana@unud.ac.id)

Received: 06-28-2025 **Revised:** 08-26-2025 **Accepted:** 09-02-2025

Citation: Sardiana, I. K., Wiguna, P. P. K., Djelantik, A. A. A. W. S., & Dewi, N. M. A. K. (2025). Community-based waste mapping in the traditional Subak irrigation systems: Evidence from Penebel District in Bali, Indonesia. *Org. Farming*, *11*(4), 227–245. https://doi.org/10.56578/of110401.

Abstract: The Subak is a traditional Balinese irrigation and farming management system rooted in socio-religious customs and ecological harmony. The sustainability of the Subak, however, is increasingly threatened by contamination from domestic, livestock, and small-scale industrial waste. This study assessed the types, sources, and practices of waste management in Penebel District in Bali with a participatory mapping approach involving surveys, field observations, and focus group discussions with farmers and local officials. Findings from 38 Subak irrigation systems revealed that 52.63% of the Subak areas were primarily affected by domestic waste while 21.05% faced mixed contamination from domestic and livestock waste. Among all, the predominant waste types included 44.74% of organic materials, such as manure and agricultural residues, and 34.21% of inorganic materials like plastics and packaging. Alarmingly, 57.89% of the Subaks left waste untreated in irrigation channels whereas 41.1% of the households disposed waste directly into drainage or irrigation ditches. Only a small portion, 21.06%, practiced composting. These informal waste practices were exacerbated by limited institutional support and deteriorated irrigation infrastructure, as 28.95% of the Subak irrigation channels were in damaged condition. In this connection, this study also shed light on the imperative for differentiated and community-based waste management strategies, aligned with the principles of organic farming. Recommended interventions included organic waste composting, structured inorganic waste collection, Awig-Awig revitalization, and environmental education to change local behaviors. The integration of participatory mapping with environmental assessment provided a practical and culturally relevant tool for empowering the Subak communities with sustainable waste and water management. Protecting the Subak landscape from waste is indispensable for safeguarding both agricultural productivity and unique cultural heritage in Bali.

Keywords: Irrigation; Participatory mapping; Subak; Waste management; Geographic Information System

1. Introduction

Characterized by the socio-agro-religious values, the Subak is a traditional and customary law-based community organization consisting of farmers who manage irrigation water for rice fields. It plays a vital role in sustaining rice production across the Bali Province. The technological coherence of the Subak system is reflected in its comprehensive water management, including the construction and operation of irrigation infrastructure as well as the coordination of operations and maintenance based on the philosophy of Tri Hita Karana, a Balinese concept emphasizing harmony among humans, nature, and the divine (Zen et al., 2024).

The Subak system in Bali, Indonesia, has been recognized as a United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage Site due to its cultural and ecological significance (Ivancov, 2025; Sardiana & Wiguna, 2023). However, the sustainability of the Subak is increasingly threatened by environmental contamination resulting from agricultural runoff, domestic waste, and tourism-related activities. These contaminants adversely affect the water quality of irrigation, soil health, and overall agricultural productivity (Ardana et al., 2024; Norken, 2019).

The Tabanan Regency, known as the "rice barn" of Bali, spans an area of 839.33 km², accounting for 14.9% of the total land area in the province. In year 2024, Tabanan Regency recorded a total area of 43,215 hectares for harvested rice field, thus marking an increase of 6.36% compared to the previous year. Tabanan is recognized as the rice granary in Bali, with irrigated rice as its main agricultural commodity. Between years 2018 and 2023, the Tabanan Regency lost approximately 2,676.61 hectares of rice fields due to land conversion for development purposes (BPS-Statistics Indonesia Tabanan Regency, 2024). This reduction represents about 3–6% of the total land area in the Regency. The key drivers of this land conversion include rapid urbanization, infrastructure expansion, and growth in the tourism sector. These factors have raised concerns over the long-term sustainability of rice production and food security in the region (Astarini et al., 2020). With population growth, the conversion of agricultural land to non-agricultural uses has accelerated and has significantly impacted the quality of the environment.

Penebel District, located in the Tabanan Regency of Bali, is recognized as one of the leading contributors to rice production in the region. Covering an area of 141.98 square kilometers and consisting of 18 villages, Penebel benefits from favorable geographic and climatic conditions for agriculture, particularly rice cultivation. A significant portion of the land, approximately 68%, is used for agriculture, including rice fields, plantations, and mixed dryland farming. According to the Department of Agriculture in the Tabanan Regency, in year 2024 Penebel reached the highest rice planting target at 7,728 hectares, which was far more than any other subdistricts (BPS-Statistics Indonesia Tabanan Regency, 2024). Moreover, Penebel is the center of organic rice farming in Tabanan. The district has actively developed organic paddy cultivation, including both white and red rice varieties. These initiatives not only increase the added value of agricultural products but also support sustainable tourism in the area (Shiotsu et al., 2015; Susilawati et al., 2025).

The conversion of rice fields in Penebel District has become a significant issue in recent years. Data indicated that between years 2016 and 2020, the Tabanan Regency experienced a decrease in the area of rice field by approximately 1,193.54 hectares, equivalent to about 5.56% of the total rice field area (Djelantik et al., 2023; Yulandari et al., 2021). In particular, in villages such as Jatiluwih in Penebel District, agricultural land has been increasingly converted into tourism-related facilities such as homestays and restaurants, thus causing degradation of the Subak-managed rice fields (Prastyadewi et al., 2020; Prastyadewi et al., 2023).

This land conversion not only reduces the extent of agricultural land but also negatively affects the environmental quality of the Subak rice fields. The conversion disrupts the traditional Subak irrigation systems, leading to a decline in the quality of irrigation water and an increase in the risks of waste contamination. Moreover, changes in land use contribute to higher amounts of domestic waste and plastic debris contaminating irrigation channels, along with degradation of the aesthetic and cultural landscape of the rice fields (Yasmita, 2025). While the traditional Subak systems are designed for sustainable water sharing and ecological balance, contemporary pressures especially unmanaged waste are disrupting this harmony. Waste from domestic, livestock, and informal industrial sources has begun to overload irrigation channels and degrade environmental functions within the Subak areas.

The impacts of this waste raise concerns about the sustainability of the Subak system, which is both a cultural heritage and a traditional water management system in Bali. Decreased environmental quality and interrupted irrigation system threaten the agricultural productivity and preservation of local cultural identity. Therefore, sustainable land management and conservation efforts are essential to maintain both the ecological function and cultural significance of rice fields in Penebel District.

Mapping plays a crucial role in identifying and understanding the extent and sources of waste in the Subak rice fields. Accurate spatial data on waste levels such as quality of irrigation water, waste types, and waste sources are essential for informed decision-making and effective environmental management (Trigunasih & Saifulloh, 2022). Without proper mapping, waste hotspots and pathways of contaminants often remain hidden; therefore, the capacity to develop targeted mitigation strategies has been limited.

Participatory mapping, which involves direct engagement of local communities in the data collection and mapping processes, emerges as the most effective approach for assessing environmental conditions in the Subak areas (Cui et al., 2024). This method not only integrates scientific and local indigenous knowledge but also empowers stakeholders by giving them a voice in monitoring and managing their environments. Community involvement ensures that the mapping reflects real-world conditions accurately and enhances the legitimacy and acceptance of subsequent conservation efforts (Parsons et al., 2021).

Furthermore, participatory mapping fosters greater awareness and responsibility among local farmers regarding the impact of waste and practices of sustainable land management. This mapping supports the preservation of both environmental quality and cultural heritage by involving the Subak members, who have deep cultural and spiritual ties to their land and irrigation systems (Delina et al., 2024). Therefore, participatory mapping stands out as a powerful tool for promoting sustainable development and environmental stewardship in the Subak-managed landscapes.

Despite its potential, the application of participatory mapping within traditional irrigation systems like the Subak remains limited. Existing studies often focused on singular aspects of environmental degradation, such as pesticide use or water scarcity, without addressing the integrated nature of waste issues in rice field ecosystems (Gava et al., 2024; Mali et al., 2023). Moreover, few studies examined the combination of multiple waste sources including domestic, livestock, and small-scale industrial waste through a community-driven spatial approach (Robinson, 2024; Si et al., 2019). his lack of comprehensive, participatory, and place-based environmental assessments in traditional agricultural systems represents a significant research gap.

This study aimed to address these gaps by integrating participatory mapping with environmental assessments to analyze waste contamination in the Subak rice fields of Penebel District, the Tabanan Regency of Bali. By involving the Subak members, local government, and local communities, the research assessed the quality of irrigation water, identified and mapped the types and distribution of waste, determined the primary sources affecting the Subak areas, and visualized contamination levels as perceived and experienced by the community. By combining scientific indicators with local knowledge, this research aspired to support inclusive, culturally grounded, and ecologically sound environmental management practices in traditional rice field systems in Bali.

2. Methodology

2.1 Location of Research

Penebel District, which is in the Tabanan Regency of Bali Province in Indonesia, covers an area of approximately 141.98 km^2 and is located at around 8.437° South latitude and 115.142° East longitude. Administratively, Penebel consists of 18 villages, including Jatiluwih, Wongaya Gede, Babahan, Senganan, and Penatahan. As of mid-2024, the estimated population of the district is approximately 55,590 people and this shows a steady increase since the 2020 census (BPS-Statistics Indonesia Tabanan Regency, 2024).

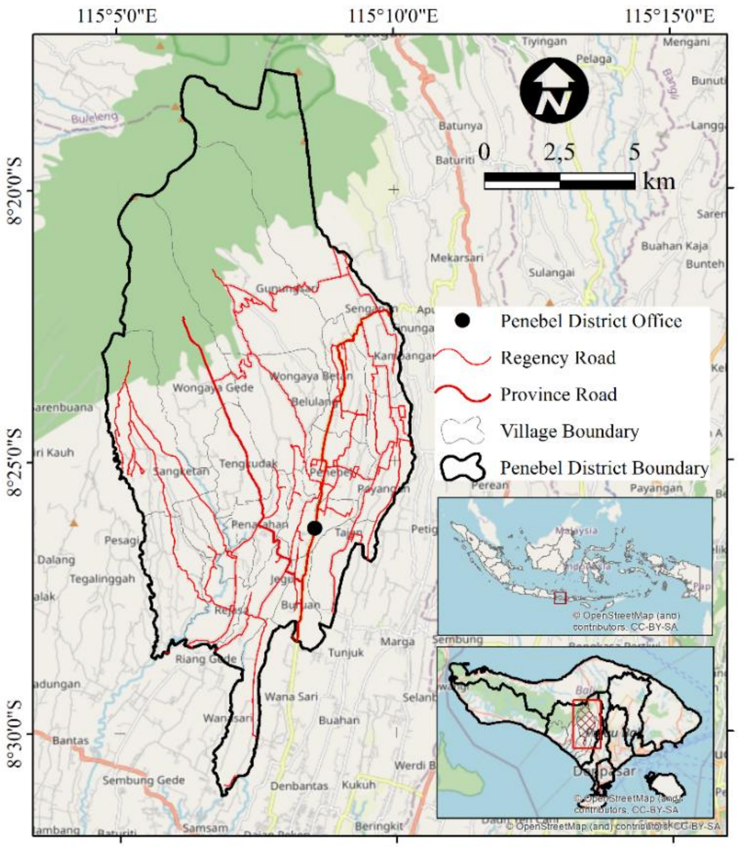


Figure 1. The location of research

Topographically, Penebel is characterized by hilly and mountainous terrain, situated on the slopes of Mount Batukaru. Elevation varies significantly, with villages such as Jatiluwih located at about 700 meters above the sea level (BPS-Statistics Indonesia Tabanan Regency, 2024). The area is also known for its terraced rice fields, particularly in Jatiluwih Village, which has been designated as a UNESCO World Heritage Site (Rahmi & Setiawan, 2020).

The population is predominantly engaged in agriculture, especially rice farming supported by fertile soils and favorable climatic conditions. In addition to farming, tourism has become an increasingly important sector, contributing to the local economy through eco-cultural tourism activities centered on natural landscapes and traditional Balinese culture (Susilawati et al., 2025). Figure 1 shows the location of this research.

2.2 Method of Data Collection

Data collection was conducted using both primary and secondary sources. Primary data were obtained through observation, surveys, interviews, and analytical techniques. Secondary data were gathered from various existing sources, including documents, references, books, journals, images, recordings, and other materials related to the research topic (Bazen et al., 2021). The methods of data collection are presented in Table 1.

Table 1. Method of data collection

No.	Data	Types of Data	Method of Data Collection	Tools/Materials Used
1	Subak identity → Name of the Subak → Location	Secondary	Data from the Department of Agriculture, research articles, spatial data	
2	Irrigation → Condition of irrigation → Quality of irrigation water	Primary	Focus group discussions, participatory mapping, and field surveys	Work map, survey form, digital camera, the Global Positioning System (GPS)
3	Waste management → Types of waste → Sources of waste → Management of waste	Primary	Focus group discussions, participatory mapping, and field surveys	Work map, survey form, digital camera, the GPS

In this study, the parameters analyzed focused on two interrelated aspects of managing the Subak-based rice field ecosystem, namely irrigation and waste management. First, in terms of irrigation, the analysis covered the condition of the irrigation network, including its completeness, functionality, and level of maintenance. These factors determine the smooth distribution of water from its sources to individual rice plots. Additionally, the quality of irrigation water was examined as the water supply might be contaminated by domestic, agricultural, or industrial waste. Assessing water quality is essential to ensure that the water used does not negatively impact rice productivity or the health of the paddy field ecosystem.

Second, regarding waste management, the study identified the types of waste present in the rice fields, such as organic waste from plant residues and livestock manure and inorganic waste from plastic, pesticide packaging, and household garbage. It also examined the sources of waste, which might originate from farming activities, surrounding settlements, or upstream runoff. The final component involved evaluating the practices of waste management, whether through traditional methods maintained by the Subak members or through policies established by the village or regional authorities. The observed management practices included the treatment of waste by a specific institution, the disposal into rivers, irrigation canals, or drainage channels, the process into compost or manure, the burial in waste pits, and any other possible methods.

This analytical approach provided a comprehensive understanding of the relationship between the availability of irrigation and the quality and waste loads of rice fields, thus forming a basis for developing sustainable Subak management strategies.

2.3 Methodology

Participatory mapping of the Subak condition in Penebel District was conducted with focus group discussions (FGD) with farmers, heads of the Subak farmer groups known as *Pekaseh*, and staff from the Department of Agriculture in the Tabanan Regency with a total of 50 participants. The FGD was conducted at the Buruan Subak meeting hall in Penebel District and interview forms were used to record data regarding the condition of each Subak. Following the interviews, field surveys were carried out to document the environmental condition, irrigation infrastructure, and land status within each Subak. The GPS and cameras were used during the surveys for spatial data collection and photographic documentation. The data gathered from the field was then mapped to analyze the specific condition of each Subak.

The significance levels of the condition of irrigation water and irrigation channels were determined based on the perceptions of respondents obtained from structured interviews and surveys. Respondents were asked to evaluate the perceived impact of each waste category on the quality of irrigation water and the sustainability of the Subak. The evaluation used adapted qualitative criteria for each local context:

- Quality of the Irrigation Water: Very Clean, Clean, and Dirty.
- Condition of the Irrigation Channels: Good, Moderate, and Damaged.

The classification was directly derived from respondents' answers and later summarized in the analysis. This perception-based approach was aligned with community-driven participatory mapping principles so as to ensure that local knowledge and experiences informed the spatial assessment. In this study, waste type was categorized into three groups based on the dominant material composition observed or reported by respondents, namely, organic, inorganic or both. Meanwhile, waste source, domestic waste management, and irrigation waste management variables were obtained by summarizing answers from the respondents during the surveys and interviews. Sources of waste described the origins of waste entering the irrigation system, such as upstream contaminants, domestic activities, livestock operations, and industrial activities. Domestic waste management reflects the handling of household waste before it potentially enters the irrigation channels, covering aspects like collection, segregation, disposal, or reuse. Irrigation waste management refers to practices undertaken by farmer groups, the Subak organizations, or related community units to clean, monitor, or prevent waste accumulation within the irrigation network.

This study collected the perceptions from local stakeholders to provide a qualitative and structured basis for evaluating the significance levels of the types and sources of waste, as well as the domestic and irrigation waste management in the studied area. Figure 2 is the flowchart of the research.

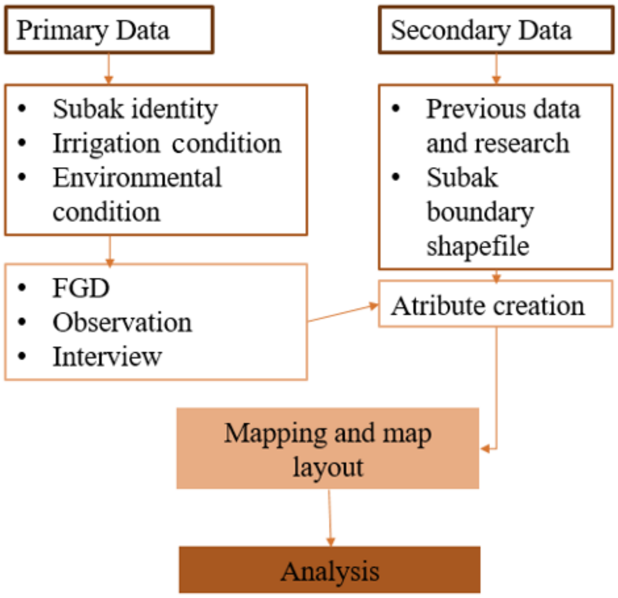


Figure 2. Flowchart of the research

3. Results and Discussion

As part of the process of data collection, FGD was conducted at the Subak Buruan Hall (Balai Subak Buruan), located in Penebel District. The FGD was attended by key stakeholders directly involved in agricultural and environmental management in the region. Participants included the heads of the Subak (Pekaseh) from various Subak organizations across Penebel District, as well as representatives from the Department of Agriculture in the Tabanan Regency.

Figure 3. Photos of the FGD

The purpose of the FGD was to gather qualitative insights and validate findings related to the condition of irrigation, practices of waste management, and challenges from the environment within the Subak system. The discussions allowed the triangulation of survey data and provided a platform for local leaders and officials to share experiences related to irrigation condition and waste management in the Subak rice fields. Figure 3 captures the scenes of the FGD.

3.1 Subak Rice Fields in Penebel District

Penebel District is one of the regions renowned for its well-preserved and functioning Subak system, a traditional Balinese irrigation and farming organization recognized as part of the UNESCO World Cultural Heritage. The Subak system integrates irrigation management, agricultural practices, and socio-religious values, providing a holistic model of sustainable agriculture rooted in local wisdom.

In Penebel, the Subak units are primarily engaged in rice cultivation, relying on gravity-fed irrigation sourced from natural springs and rivers that flow from the central highlands of Bali, including Mount Batukaru. The Subak in this region is characterized by terraced rice fields, which are not only agriculturally productive but also significant to the cultural and ecological landscapes of the island.

Each Subak is governed by a head farmer known as the Pekaseh, who is elected by local members and is responsible for coordinating irrigation schedules, resolving water disputes, and maintaining the infrastructure of the canals. Decision-making in the Subak system is traditionally democratic and often tied to rituals conducted at the Subak temples, Pura Ulun Subak, so as to reflect the spiritual foundation of the system.

Despite its strengths, the Subak system in Penebel faces growing challenges such as increasing waste, declining water quality, degrading infrastructure, and changing land-use patterns. The alarming presence of domestic, industrial, and agricultural waste, particularly plastic and chemical runoff, has raised concerns about the long-term sustainability of both irrigation and agricultural productivity in the region. Nonetheless, the Subak communities in Penebel remain actively involved in maintaining their systems with support from local government agencies and civil society, serving as models of community-based and environmentally integrated management of water and land.

The Subak system in Penebel District, the Tabanan Regency of Bali, is distributed across multiple villages, thus reflecting a strong integration of traditional irrigation practices into the agricultural landscape of the region. Based on the survey data, there are a total of 38 Subak units associated with the management of rice fields in 21 villages and Hamlets (Banjar) across the district.

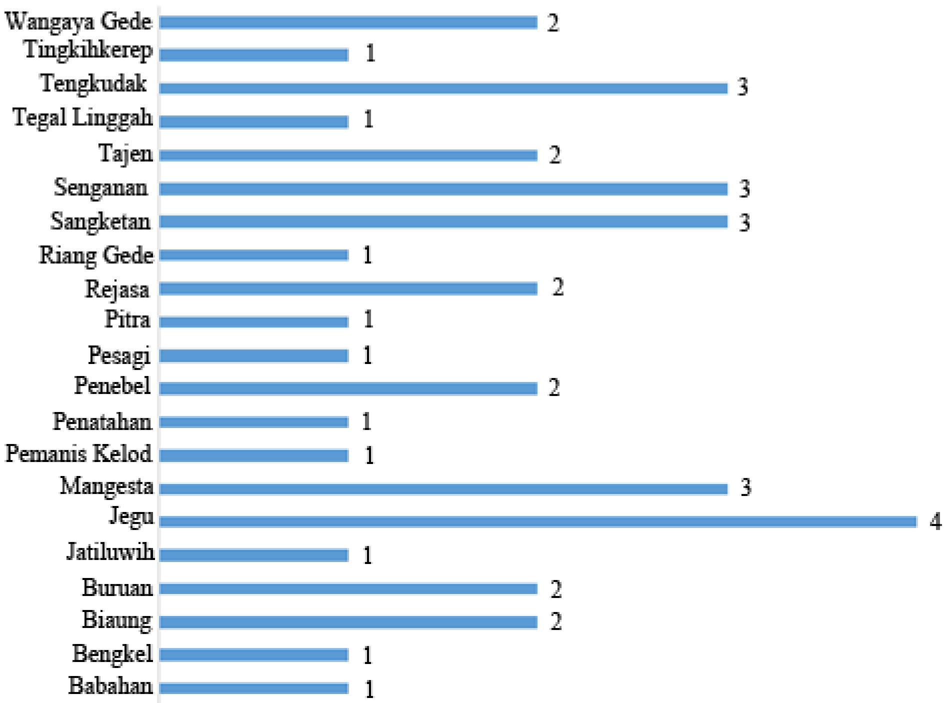
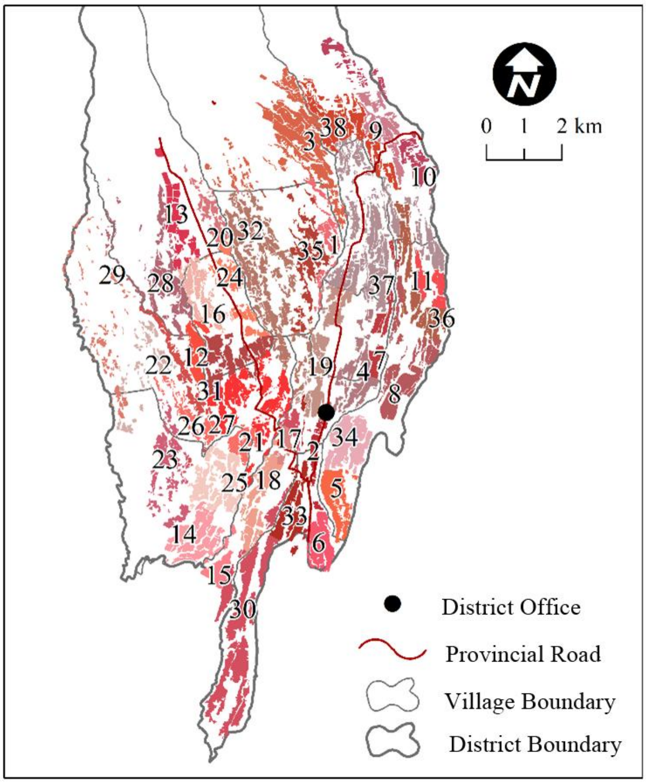


Figure 4. Number of the Subak rice fields per village in Penebel District

The village of Jegu holds the highest number of 4 Subak units, thus indicating a dense agricultural activity and a well-established irrigation network. Following this, the villages of Mangesta, Sangketan, Senganan, and

Tengkudak have 3 Subak units each and they play a significant role in local food production and traditional land stewardship. Several villages, namely Biaung, Buruan, Penebel, Rejasa, Tajen, and Wangaya Gede, have 2 Subak units each, contributing to medium-scale Subak-based rice cultivation in the region. Meanwhile, a number of villages such as Babahan, Bengkel, Jatiluwih, Pemanis Kelod, Penatahan, Pesagi, Pitra, Riang Gede, Tegal Linggah, and Tingkihkerep are associated with 1 Subak unit only, hence representing smaller-scale Subak operations to maintain strong cultural and ecological significance. This distribution highlights the diversity of the Subak organizations in Penebel District, with some villages maintaining multiple Subak units due to their favorable topography, larger irrigated rice areas, and more intensive agricultural activities.

Despite differences in scale, each Subak plays a vital role in sustaining environmentally conscious and community-based rice farming practices aligned with the principles of traditional Balinese agriculture. Figure 4 lists the number of the Subak rice fields per village in Penebel District. The map in Figure 5 exhibits the distribution of the Subak rice fields in Penebel District.



No.	Subak Name	Desa (Village)/Namjar (Hamlets)
1	Subak Wangaye Betan	Mangesta
2	Subak Petung	Buruan
3	Subak Jatiluwih	Jatiluwih
4	Subak Serason	Pitra
5	Subak Cepik	Tajen
6	Subak Buruan	Buruan
7	Subak Aya Sunantaya	Penebel
8	Subak Kebon	Biaung
9	Subak Rum	Senganan
10	Subak Srinadi	Senganan
11	Subak Abian Sawan	Pemanis Kelod
12	Subak Tingkih Kerep	Tingkihkerep
13	Subak Kelocing	Wangaya Gede
14	Subak Rejasa	Rejasa
15	Subak Caguh Tempek Ngis	Jegu
16	Subak Puakan	Tengkudak
17	Subak Sigaran	Jegu
18	Subak Jegu	Jegu
19	Subak Penebel	Penebel
20	Subak Bedugul	Wangaya Gede
21	Subak Sangkatan	Sangkatan
22	Subak Anyar Sangkatan	Sangkatan
23	Subak Pesagi	Pesagi
24	Subak Pancoran Sari	Tengkudak
25	Subak Srigumana	Rejasa
26	Subak Tegallinggah	Tegal Linggah
27	Subak Penatahan	Penatahan
28	Subak Piak	Bengkel
29	Subak Puring	Sangkatan
30	Subak Riang	Riang Gede
31	Subak Tengkudak	Tengkudak
32	Subak Piling	Mangesta
33	Subak Benana	Jegu
34	Subak Tajen	Tajen
35	Subak Kedampal	Mangesta
36	Subak Aya Pemanis	Biaung
37	Subak Aya Babahan	Babahan
38	Subak Merta	Senganan

Figure 5. Map of the Subak rice fields in Penebel District

3.2 Irrigation Condition in Penebel District

Assessment of the irrigation condition in the Subak areas of Penebel District revealed notable variation in both cleanliness and structural quality. Based on the results of the survey, 0% of the Subak units reported very clean irrigation systems. A majority, 65.79% of the Subaks (25 Subaks) classified their irrigation water as clean whereas the remaining 34.21% (13 Subaks) reported dirty. Based on the data, the quality of irrigation water in most Subak was classified as clean. This indicated that the water flowing through the irrigation channels was free from major pollutants and suitable for supporting agricultural activities, especially rice cultivation. The classification of cleanliness reflected that, at the local level, water management practices and surrounding environmental condition were relatively well maintained.

Several villages such as Senganan Village (Subak Rum and Subak Merta), Sangketan Village (Subak Sangketan, Subak Anyar Sangketan, and Subak Puring), and Tengkudak Village (Subak Puakan, Subak Pancoran Sari, and Subak Tengkudak), had multiple Subaks with clean irrigation water. This consistency showed that the condition of water sources and distribution systems in these areas was still reliable.

Other examples including Jegu Village (Subak Caguh Tempek Ngis, Subak Benana, and Subak Sigaran), Wangaya Gede Village (Subak Keloncing and Subak Bedugul), and Mangesta Village (Subak Wangaye Betan and Subak Kedampal) demonstrated good quality in their irrigation water across more than one Subak. The widespread presence of clean water in these villages highlighted the importance of continued efforts to protect upstream water sources and prevent contamination from domestic or agricultural waste.

On the other hand, 13 Subaks were identified as having dirty irrigation water. Some examples were Subak Piling (Mangesta Village), Subak Petung (Buruan Village), Subak Tegallinggah (Tegal Linggah Village), and Subak Jatiluwih (Jatiluwih Village). The presence of dirty water in these Subaks suggested contamination from various sources, involving domestic waste, agricultural runoff, and practices of insufficient waste management in the surrounding environment.

Interestingly, some villages showed a mixed condition. For instance, Senganan Village, Subak Rum, and Subak Merta had clean irrigation water while Subak Srinadi was categorized as dirty. Similarly, in Jegu Village, certain Subaks such as Subak Caguh Tempek Ngis and Subak Benana were classified as clean whereas Subak Jegu and Subak Sigaran experienced dirty water condition. These mixed results indicated that variations in local water sources, waste management, and practices of land use played a significant role in determining the quality of irrigation water.

Overall, the findings highlighted that while the majority of the Subaks still enjoyed clean irrigation water, a considerable portion faced challenges with declining water quality. This situation underlined the urgent need for integrated management of irrigation systems, particularly through protecting upstream water sources, strengthening waste management systems, and enhancing community awareness to minimize risks of waste. Without intervention, the Subaks currently experiencing dirty irrigation water might see further decline, which could potentially threaten the sustainability of rice farming in these cultural landscapes.

In total, there were 25 Subaks with clean irrigation water. This condition served as strong evidence to most of the irrigation systems in the studied area with effectively functioning and less contaminated water sources. However, regular monitoring is still necessary to ensure that future pressures such as population growth, agricultural intensification, and land-use changes do not deteriorate this favorable condition. Table 2 shows the quality of the irrigation water in Penebel District.

Table 2. Quality of the irrigation water in Penebel District

Categories	The Subak (Village)	Total Number of the Subak	Percentage (%)
Clean	Subak Rum (Senganan), Subak Sangketan (Sangketan), Subak Aya Babahan (Babahan), Subak Tingkih Kerep (Tingkihkerep), Subak Puakan (Tengkudak), Subak Serason (Pitra), Subak Pesagi (Pesagi), Subak Piak (Bengkel), Subak Buruan (Buruan), Subak Kebon (Biaung), Subak Keloncing (Wangaya Gede), Subak Caguh Tempek Ngis (Jegu), Subak Anyar Sangketan (Sangketan), Subak Pancoran Sari (Tengkudak), Subak Puring (Sangketan), Subak Riang (Riang Gede), Subak Tengkudak (Tengkudak), Subak Benana (Jegu), Subak Cepik (Tajen), Subak Sigaran (Jegu), Subak Bedugul (Wangaya Gede), Subak Merta (Senganan), Subak Wangaye Betan (Mangesta), Subak Abian Sawan (Pemanis Kelod), Subak Kedampal (Mangesta)	25	65.79%
Dirty	Subak Piling (Mangesta), Subak Petung (Buruan), Subak Tegallinggah (Tegal Linggah), Subak Srinadi (Senganan), Subak Rejasa (Rejasa), Subak Srigumana (Rejasa), Subak Jatiluwih (Jatiluwih), Subak Aya Sunantaya (Penebel), Subak Jegu (Jegu), Subak Penebel (Penebel), Subak Penatahan (Penatahan), Subak Tajen (Tajen), Subak Aya Pemanis (Biaung)	13	34.21%
	Total	38	100%

Although the results of the survey indicated that several Subak areas in Penebel District received “clean” irrigation water, it was important to contextualize the meaning of “clean” in the traditional agricultural irrigation systems. In this context, clean water referred to water that was suitable for irrigation without containing harmful pollutants, which could damage crops or soil structures.

Moreover, small amounts of floating debris such as dry leaves or biodegradable plant matter might still be present in these channels. These materials were generally considered non-hazardous and often filtered out through traditional weir systems or allowed to decompose naturally in the field. However, water categorized as clean typically lacked significant levels of plastic waste, chemical effluents, and livestock waste, all of which were indicators of contamination.

Therefore, in the context of the Subak irrigation, clean water does not equate to potable or drinking water standards, but rather denotes water quality that supports safe, productive, and sustainable rice cultivation without introducing excessive contaminants into the ecosystem. This distinction is essential to the perception of the farming community as well as technical assessments of the quality of irrigation water in rural agrarian settings.

Importantly, the presence of dirty irrigation water is not solely attributed to natural waste such as fallen leaves. A significant contributing factor is the widespread presence of non-biodegradable waste, particularly plastic packaging, used bottles, and livestock waste, including manure from pigs and poultry. These pollutants, often disposed of directly into irrigation canals or nearby drainage channels, accumulate and degrade water quality, especially in downstream Subak areas. This contamination not only affects agricultural productivity but also poses ecological and health risks to the surrounding environment.

Only 10.53% of the physical infrastructure, i.e., 4 Subaks, reported irrigation systems in good condition. The majority, 60.53%, of the system, i.e., 23 Subaks were categorized as being in moderate condition while 28.95%, 11 Subaks, were considered damaged. The Subak with well-functioning irrigation channels includes Subak Rum in Senganan Village, Subak Sangketan in Sangketan Village, Subak Piling in Mangesta Village, and Subak Aya Babahan in Babahan Village. The good condition of the irrigation systems in these four Subaks indicated that water distribution remained efficient and reliable in supporting agricultural activities, particularly rice fields that depended heavily on sustainable water supply. Table 3 suggests the condition of the irrigation channels in Penebel District.

Table 3. Condition of the irrigation channels in the Tabanan Regency

Condition of the Irrigation Channels	The Subak (Village)	Total Number of the Subak	Percentage (%)
Good	Subak Aya Babahan (Babahan Village), Subak Piling (Mangesta Village), Subak Rum (Senganan Village), Subak Sangkan (Sangkanan Village)	4	10.53%
Moderate	Subak Abian Sawan (Pemanis Kelod Village), Subak Anyar (Sangkanan Village), Subak Aya Pemanis (Biaung Village), Subak Aya Sunantaya (Penebel Village), Subak Bedugul (Wangaya Gede Village), Subak Benana (Jegu Village), Subak Buruan (Buruan Village), Subak Caguh Tempek Ngis (Jegu Village), Subak Cepik (Tajen Village), Subak Jegu (Jegu Village), Subak Kebon (Biaung Village), Subak Keloncing (Wangaya Gede Village), Subak Merta (Senganan Village), Subak Pancoran Sari (Tengkudak Village), Subak Penatahan (Penatahan Village), Subak Penebel (Penebel Village), Subak Puring (Sangkanan Village), Subak Riang (Riang Gede Village), Subak Sigaran (Jegu Village), Subak Tajan (Tajen Village), Subak Tengkudak (Tengkudak Village), Subak Wangaye Betan (Mangesta Village)	23	60.53%
Damaged	Subak Jatiluwih (Jatiluwih Village), Subak Pesagi (Pesagi Village), Subak Petung (Buruan Village), Subak Piak (Bengkel Village), Subak Puakan (Tengkudak Village), Subak Rejasa (Rejasa Village), Subak Serason (Pitra Village), Subak Srigumana (Rejasa Village), Subak Srinadi (Senganan Village), Subak Tegallinggah (Tegal Linggah Village), Subak Tingkih Kerep (Tingkihkerep Village)	11	28.95%
	Total	38	100%

Based on the available data, irrigation channels classified as being in moderate condition were distributed across almost all villages in the studied area. In general, the moderate condition indicated that the channels were still functioning to deliver water to agricultural lands, but their performance was not optimal. This condition was usually marked by minor damage to the structures, sedimentation that obstructed water flow, or small leaks that reduced the amount of water reaching the rice fields.

Several villages had more than one Subak with irrigation channels in moderate condition and these included Jegu Village (Subak Caguh Tempek Ngis, Subak Benana, Subak Sigaran, and Subak Jegu), Sangketan Village (Subak Anyar Sangketan and Subak Puring), Wangaya Gede Village (Subak Keloncing and Subak Bedugul), Penebel Village (Subak Aya Sunantaya and Subak Penebel), and Tajen Village (Subak Cepik and Subak Tajen). Overall, there were 23 Subaks with irrigation channels in moderate condition. This situation highlighted the need for regular maintenance and minor repairs to prevent further deterioration. If left unaddressed, declining quality of the irrigation channels could affect water distribution, reduce agricultural productivity, and ultimately threaten the sustainability of the Subak system as a cultural heritage and a foundation of local food security.

Eleven Subaks were recorded with damaged irrigation channels; for instance, Subak Petung (Buruan Village), Subak Tingkih Kerep (Tingkihkerep Village), Subak Puakan (Tengkudak Village), Subak Tegallinggah (Tegal Linggah Village), and Subak Jatiluwih (Jatiluwih Village), known as a UNESCO World Heritage cultural landscape. The damage to the irrigation systems in these Subaks led to several issues like reduction in the efficiency of water distribution, leakage or water loss before reaching farmland, and potential decline in agricultural productivity due to uneven water availability.

Overall, this condition reflected a disparity in the maintenance and functionality of irrigation channels across the Subaks. The Subaks with well-maintained systems had the potential to sustain local food security through continued rice production whereas those with damaged channels faced significant challenges in maintaining productivity. If these damages are not promptly addressed, in the long term, they may threaten the sustainability of the Subak system as both a cultural heritage and a key foundation of food security in Bali.

The deterioration of irrigation infrastructure can be attributed to two key factors: limited government funding for maintenance and rehabilitation, and financial constraints faced by local farmers. These limitations hinder timely repairs and improvements, exacerbating the decline in irrigation functionality and further reducing the efficiency of water delivery across the Subak landscape.

Given these findings, urgent attention is required to improve both the sanitation and structural condition of the irrigation systems via a combination of policy interventions, community-based maintenance efforts, and sustainable funding mechanisms. Addressing these challenges is essential for safeguarding the Subak system and ensuring long-term agricultural sustainability in Penebel District. Figure 6 displays the condition of irrigation channels and water quality in Penebel District. Figure 7 presents the maps of irrigation channels and water quality in Penebel District.

Figure 6. Pictures showing the condition of the irrigation channels in Penebel District

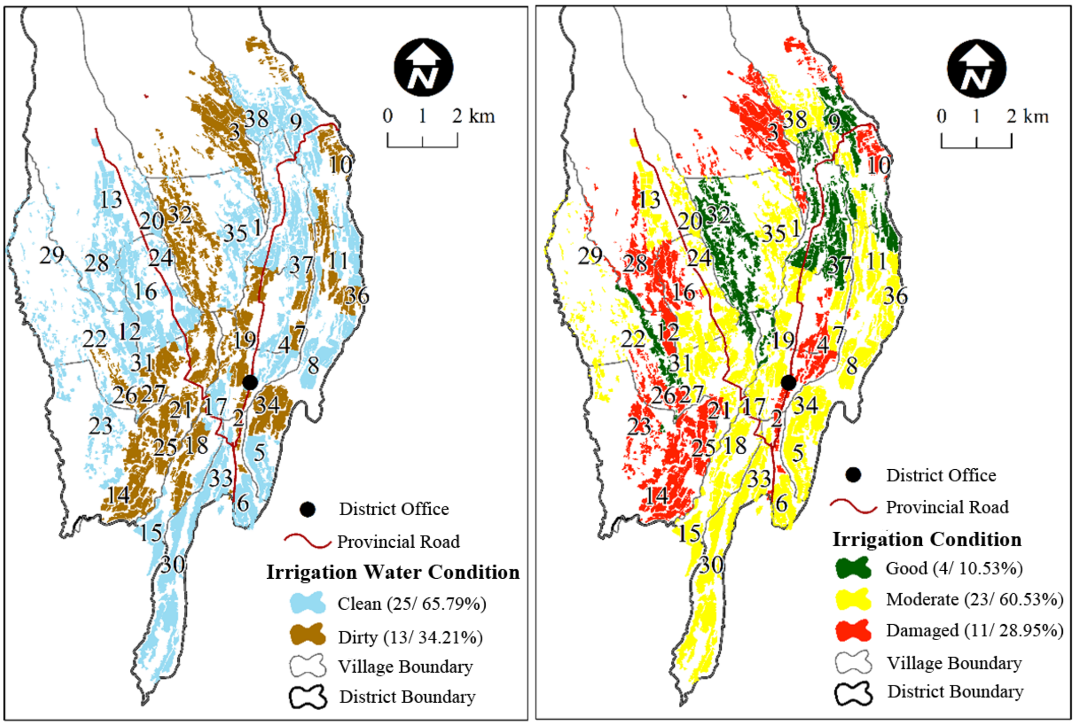


Figure 7. Maps showing the condition of irrigation water (left) and irrigation channels (right)

In the Subak areas of Penebel District, the most dominant sources of waste are domestic household waste and industrial pollutants such as used plastic bottles and packaging. Agricultural activities also contribute significantly to the continuous adoption of chemical pesticides for pest and disease control. Livestock-related waste include pig manure and dead poultry, often discarded into nearby rivers or irrigation canals. Other pollutants, though less significant in quantity, are originated upstream and are carried into the Subak areas via river flow.

Solid waste in the area is predominantly composed of organic and inorganic materials. The most environmentally concerning organic waste is livestock manure, particularly from pigs and chickens. Inorganic waste, especially plastic and packaging materials, is found to be widespread across nearly all Subak regions in Penebel. Metal waste and similar materials are present but limited to specific areas.

Only a few Subak units in Penebel District meet both criteria of clean water and well-maintained channels. Specifically, Subak Rum in Senganan Village and Subak Aya Babahan in Babahan Village demonstrated exemplary condition, with water quality classified as clean and irrigation channels in good condition. This indicated that these communities had been relatively successful in managing both the physical infrastructure of their irrigation systems and the surrounding environment; this helped ensure adequate and safe water supply for agricultural activities. The other Subak units might have either clean water or well-maintained channels, but not both, thus highlighting the importance of integrated management practices that address both water quality and infrastructure maintenance to sustain agricultural productivity and environmental health.

On the other hand, Subak Jatiluwih, a UNESCO World Heritage site, is facing increasing concern due to deteriorating irrigation channels and declining water quality. The situation is further exacerbated by expanding tourism infrastructure such as hotels, restaurants, and other facilities, which raises the risk of waste contamination in the irrigation system. These challenges threaten both agricultural productivity and cultural and environmental integrity, which emphasizes the global significance of Subak Jatiluwih. To preserve the functionality and heritage value of this iconic Subak system, immediate interventions are needed to rehabilitate irrigation channels and enhance waste management practices, alongside careful monitoring of the impact on tourism.

3.3 Waste Management in the Subak System

The analysis of waste sources within the Subak irrigation systems revealed a diverse range of pressures that threatened both water quality and agricultural sustainability. Broadly speaking, three main sources of waste were identified: upstream waste, domestic (household) waste, and sectoral waste from livestock and industry. Table 4 categorizes the sources of waste in the Subak areas in Penebel District.

Table 4. Sources of waste in the Subak areas in Penebel District

Sources of Waste	The Subak (Village)	Total Number of the Subak	Percentage (%)
Domestic waste	Sangkan (Sangkan), Tingkih Kerep (Tingkih Kerep), Puakan (Tengkudak), Pesagi (Pesagi), Piak (Bengkel), Kebon (Biaung), Keloncing (Wangaya Gede), Caguh Tempek Ngis (Jegu), Anyar Sangkan (Sangkan), Puring (Sangkan), Tengkudak (Tengkudak), Bedugul (Wangaya Gede), Wangaye Betan (Mangesta), Abian Sawan (Pemanis Kelod), Kedampal (Mangesta), Piling (Mangesta), Petung (Buruan), Tegallinggah (Tegal Linggah), Jegu (Jegu), Penebel (Penebel)	20	52.63%
Domestic + livestock waste	Rum (Senganan), Aya Babahan (Babahan), Pancoran Sari (Tengkudak), Rejasa (Rejasa), Srigumana (Rejasa), Aya Sunantaya (Penebel), Penatahan (Penatahan), Aya Pemanis (Biaung)	8	21.05%
Livestock waste	Cepik (Tajen), Sigaran (Jegu), Merta (Senganan), Srinadi (Senganan), Benana (Jegu)	5	13.16%
Domestic + industrial waste	Benana (Jegu)	1	2.63%
Domestic + livestock + industrial waste	Jatiluwih (Jatiluwih)	1	2.63%
Upstream waste	Serason (Pitra), Buruan (Buruan), Riang (Riang Gede)	3	7.89%
	Total	38	100%

Analyzing the sources of waste across Subaks in the studied area revealed an explicit dominance of domestic waste as the primary contributor to degraded water quality. Out of a total of 38 Subaks, 20 Subaks, 52.63%, were primarily affected by domestic waste. These included Sangkan (Sangkan), Tingkih Kerep (Tingkih Kerep), Puakan (Tengkudak), Pesagi (Pesagi), Piak (Bengkel), Kebon (Biaung), Keloncing (Wangaya Gede), Caguh Tempek Ngis (Jegu), Anyar Sangkan (Sangkan), Puring (Sangkan), Tengkudak (Tengkudak), Bedugul (Wongaya Gede), Wangaye Betan (Mangesta), Abian Sawan (Pemanis Kelod), Kedampal (Mangesta), Piling (Mangesta), Petung (Buruan), Tegallinggah (Tegal Linggah), Jegu (Jegu), and Penebel (Penebel). The predominance of household waste indicated that rapid population growth and dense residential settlements near irrigation channels were directly linked to the decline in the quality of irrigation water.

A significant secondary source came from a combination of domestic and livestock waste, which had its impact on 21.05% of the system, i.e., 8 Subaks. These are Rum (Senganan), Aya Babahan (Babahan), Pancoran Sari (Tengkudak), Rejasa (Rejasa), Srigumana (Rejasa), Aya Sunantaya (Penebel), Penatahan (Penatahan), and Aya Pemanis (Biaung). In these Subaks, problems of household wastewater were compounded by unmanaged waste from livestock, especially cattle and pigs and the waste was often discharged directly into the irrigation systems. The overlapping contamination highlighted a compounded threat to both water quality and agricultural productivity. In addition, 5 Subaks, 13.16% of the system, were predominantly affected by livestock waste, namely Cepik (Tajen), Sigaran (Jegu), Merta (Senganan), Srinadi (Senganan), and Benana (Jegu). These areas were characterized by intense livestock activities and insufficient manure management, which intensified the risks of water contamination. Industrial waste, although less widespread, was still a matter of concern.

One Subak (2.63% of the system), Benana (Jegu), was contaminated by both domestic and industrial waste, while another Subak (2.63% of the system), Jatiluwih (Jatiluwih), was affected simultaneously by domestic, livestock, and industrial waste. Although industrial waste appears in limited cases, its presence is critical since it often involves hazardous and non-biodegradable pollutants that pose long-term risks. Furthermore, 3 Subaks (7.89% of the system), Serason (Pitra), Buruan (Buruan), and Riang (Riang Gede), were impacted by sources of upstream waste. Their downstream locations in other irrigation and settlement areas resulted in their vulnerability to waste originating outside their own boundaries, thus underscoring the interconnectivity of the Subak irrigation systems.

The findings confirmed that domestic waste was the leading waste source, affecting more than half, 52.63%, of the Subaks, followed by domestic-livestock waste of 21.05%, livestock waste alone of 13.16%, upstream waste of 7.89%, and mixed domestic-industrial waste of 5.26%. These results emphasized the urgency for integrated waste management policies, with particular focus on domestic wastewater, alongside improved handling of livestock waste and strict monitoring of industrial discharges. Local regulations, coupled with community-based initiatives, were essential to safeguard the quality of irrigation water and ensure the long-term sustainability of Subak agriculture.

Table 5 indicates the types of waste in the Subak areas in Penebel District. The results revealed that the primary source of waste in the Subak irrigation system was organic waste. Out of the 38 Subaks surveyed, 17 Subaks, i.e., 44.74% were polluted by organic waste. These included Sangketan (Sangketan Village), Anyar Sangketan (Sangketan), Biaung (Biaung), Penatahan (Penatahan), Piling (Mangesta), Rejasa (Rejasa), Srinadi (Senganan), Srigumana (Rejasa), Tajen (Tajen), Tegallinggah (Tegal Linggah), Pemanis (Biaung), Ayah Sunantaya (Penebel), Penebel (Penebel), Jegu (Jegu), Petung (Buruan), Jatiluwih (Jatiluwih), and Gunung Sari (Tengkudak). Most of the organic waste came from leaves, branches, and household residues entering the irrigation channels. While organic waste is biodegradable, excessive accumulation disrupts water flow and contributes to channel siltation.

Table 5. Types of waste in the Subak areas in Penebel District

Types of Waste	The Subak (Village)	Total Number of the Subak	Percentage (%)
Organic waste	Sangketan (Sangketan), Tingkih Kerep (Tingkihkerep), Puakan (Tengkudak), Pesagi (Pesagi), Kebon (Biaung), Keloncing (Wangaya Gede), Caguh Tempek Ngis (Jegu), Anyar Sangketan (Sangketan), Puring (Sangketan), Tengkudak (Tengkudak), Wangaye Betan (Mangesta), Abian Sawan (Pemanis Kelod), Kedampal (Mangesta), Aya Pemanis (Biaung), Jatiluwih (Jatiluwih), Sigaran (Jegu), Merta (Senganan)	17	44.74%
Inorganic waste	Serason (Pitra), Buruan (Buruan), Riang (Riang Gede), Piak (Bengkel), Bedugul (Wongaya Gede), Piling (Mangesta), Petung (Buruan), Penebel (Penebel), Rum (Senganan), Pancoran Sari (Tengkudak), Rejasa (Rejasa), Cepik (Tajen), Tajen (Tajen)	13	34.21%
Organic & inorganic waste	Tegallinggah (Tegal Linggah), Jegu (Jegu), Benana (Jegu), Aya Babahan (Babahan), Srigumana (Rejasa), Aya Sunantaya (Penebel), Penatahan (Penatahan), Srinadi (Senganan)	8	21.05%
	Total	38	100%

In contrast, inorganic waste was found in 13 Subaks (34.21% of the system), namely Batannyuh (Batannyuh), Besikalung (Besikalung), Kelepundung (Senganan), Lebah Muncung (Rejasa), Munduk Temu (Munduk Temu), Payangan (Penatahan), Penarukan (Penarukan), Pucaksari (Munduk Temu), Saren Kauh (Senganan), Tengkudak (Tengkudak), Tengkudak Anyar (Tengkudak), Umacandi (Penebel), and Wongaya Betan (Wongaya Betan). This category was mostly composed of plastics, bottles, and food packaging, which are non-biodegradable. The presence of such materials indicated the increasing influence of modern consumption patterns, particularly the widespread use of plastic, which directly threatened the ecological balance of the Subak irrigation system.

The third category involved the combined organic and inorganic waste identified in 8 Subaks (21.05% of the system). The Subaks were Apuan (Apuan), Biaung Anyar (Biaung), Gunung Sari Anyar (Tengkudak), Kesiut (Kesiut), Lebah Pangkung (Rejasa), Pacung (Pacung), Sangketan Anyar (Sangketan), and Tengkudak Anyar Kangin (Tengkudak). The coexistence of both organic and inorganic pollutants highlighted a more complicated environmental challenge, as natural organic loads were now compounded by anthropogenic pressures. The Subaks in this category were generally located near densely populated settlements or areas with intense human activities, thus increasing their vulnerability to waste pollution.

The findings demonstrated that waste pollution in the Subak was no longer solely depended on natural factors like organic waste, but increasingly on external and human-induced factors like inorganic and mixed waste. With nearly half of the Subaks contaminated by organic waste, one-third by inorganic waste, and one-fifth by mixed pollutants, waste management emerged as the most pressing challenge in sustaining the Subak irrigation system. While organic waste tended to decompose naturally, inorganic and mixed pollutants required serious interventions such as policy enforcement, strengthened community-based institutions, and active participation of local residents in reducing single-use plastics and improving integrated waste management practices. Figure 8 shows spatial distribution of the sources and types of waste across the Subak areas in Penebel District.

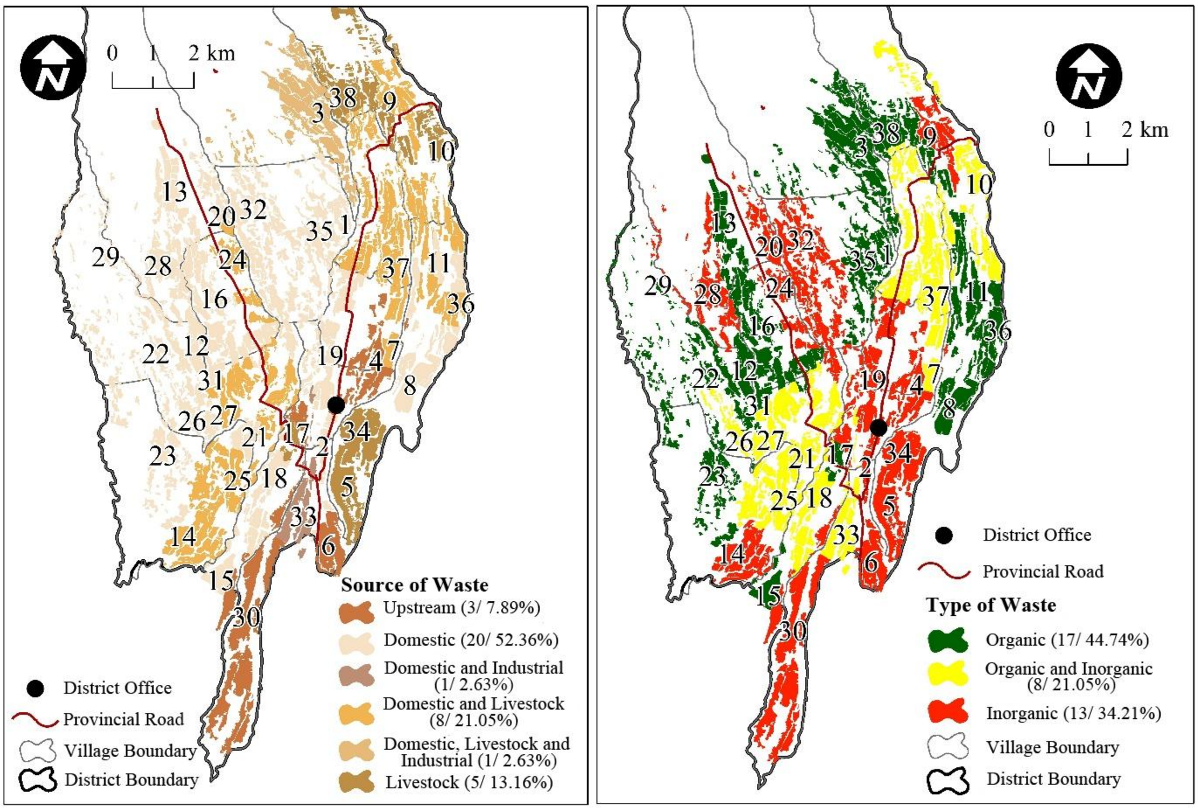


Figure 8. Maps showing the sources of waste (left) and the types of waste (right)

The residents in these areas tended to dispose their waste into natural water bodies, including rivers, irrigation ditches, drainage channels, and ponds. While others repurposed organic waste as compost or fertilizer, the handling of inorganic waste remained inadequate. Plastic waste, bottles, and packaging were frequently discarded indiscriminately, posing a significant threat to the environment. Some residents burnt their waste, which carried environmental and health risks. Nonetheless, local values and practices implying the potential for community-based waste management rooted in local wisdom, discouraged the disposal of waste into water bodies in certain Subak communities. Institutional waste management remained rare in these areas. Therefore, establishing more structured and organized waste management systems was crucial to support environmental conservation in the Subak regions, as part of the broader goal of achieving sustainable agriculture. Table 6 shows the management of the irrigation waste in the Subak areas in Penebel District.

The results of this study indicated a prevailing lack of structured waste management in the Subak irrigation systems of Penebel District. A substantial portion, 57.89% of the Subak units, i.e., 22 Subaks reported that waste was left untreated in irrigation channels. This practice was found in Subak Sangkatan (Sangkatan), Subak Pesagi (Pesagi), Subak Piak (Bengkel), Subak Kebon (Biaung), Subak Tengkulak (Tengkudak), Subak Piling (Mangesta), Subak Jegu (Jegu), Subak Penebel (Penebel), Subak Benana (Jegu), Subak Rum (Senganan), Subak Aya Babahan (Babahan), Subak Pancoran Sari (Tengkudak), Subak Rejasa (Rejasa), Subak Srigumana (Rejasa), Subak Aya Sunantaya (Penebel), Subak Penatahan (Penatahan), Subak Jatiluwih (Jatiluwih), Subak Cepik (Tajen), Subak Sigaran (Jegu), Subak Merta (Senganan), Subak Srinadi (Senganan), and Subak Tajen (Tajen). The direct discharge of untreated wastewater into irrigation systems presented potential risks to downstream water quality and agricultural productivity.

Table 6. Management of the irrigation waste in the Subak areas in Penebel District

Management of the Irrigation Waste	The Subak (Village)	Total Number of the Subak	Percentage (%)
Discarded on bare land	Serason (Pitra), Tingkih Kerep (Tingkihkerep), Puakan (Tengkudak), Keloncing (Wangaya Gede), Caguh Tempek Ngis (Jegu), Anyar Sangketan (Sangketan), Puring (Sangketan), Bedugul (Wongaya Gede), Wangaye Betan (Mangesta), Petung (Buruan), Tegallinggah (Tegal Linggah), Aya Pemanis (Biaung)	12	31.58%
Collected in waste pits	Buruan (Buruan), Riang (Riang Gede), Abian Sawan (Pemanis Kelod), Kedampal (Mangesta)	4	10.53%
Untreated	Sangkan (Sangketan), Pesagi (Pesagi), Piak (Bengkel), Kebon (Biaung), Tengkudak (Tengkudak), Piling (Mangesta), Jegu (Jegu), Penebel (Penebel), Benana (Jegu), Rum (Senganan), Aya Babahan (Babahan), Pancoran Sari (Tengkudak), Rejasa (Rejasa), Srigumana (Rejasa), Aya Sunantaya (Penebel), Penatahan (Penatahan), Jatiluwih (Jatiluwih), Cepik (Tajen), Sigaran (Jegu), Merta (Senganan), Srinadi (Senganan), Tajen (Tajen)	22	57.89%
	Total	38	100%

Overall, the predominant disposal of untreated wastewater into irrigation canals highlighted the urgent need for improved wastewater management strategies within the Subak systems. While some Subaks have taken steps toward safer practices through the construction of storage ponds, the majority continue to rely on methods that may compromise both environmental and human health. Strengthening institutional support, introducing low-cost treatment technologies, and raising awareness among farmers are crucial steps to enhance the sustainability of water management in the traditional Subak irrigation network.

In many of these cases, there exists a perception among farmers that the waste will eventually be flushed downstream, where it accumulates and is later removed manually or allowed to settle at the end of the irrigation network. This approach, however, creates temporary blockages, reduces water quality, and increases sedimentation, hence compromising the efficiency and ecological balance of the irrigation system.

Meanwhile, 12 Subaks (31.58% of the system) managed their irrigation wastewater by disposing it into empty land without proper treatment. Examples included Subak Serason (Pitra), Subak Tingkih Kerep (Tingkihkerep), Subak Puakan (Tengkudak), Subak Keloncing (Wangaya Gede), Subak Caguh Tempek Ngis (Jegu), Subak Anyar Sangkatan (Sangkatan), Subak Puring (Sangkatan), Subak Bedugul (Wangaya Gede), Subak Wangaye Betan (Mangesta), Subak Petung (Buruan), Subak Tegallinggah (Tegal Linggah), and Subak Aya Pemanis (Biaung). Although this approach could temporarily remove wastewater from irrigation channels, it might lead to soil degradation or contamination of groundwater resources. This method was generally considered to be a temporary holding strategy by local communities. In practice, the waste typically consisting of dry organic matter and household refuse was burned periodically and the emissions released contributed to air pollution and loss of potential organic materials that could otherwise be composted or reused productively.

10.53% of the system, i.e., 4 Subaks, reported efforts to collect and store waste, particularly organic waste, in a designated area or container; they were Subak Buruan (Buruan), Subak Riang (Riang Gede), Subak Abian Sawan (Pemanis Kelod) and Subak Kedampal (Mangesta). For instance, Subak Kedampal (Mangesta) adopted a pond system for wastewater collection. In these cases, farmers expressed intentions to convert the waste into compost, either for direct application to rice fields or support to home gardens. This reflected growing awareness of the value of organic waste as a soil amendment and a shift toward more sustainable and closed-loop agricultural practices.

The management of domestic waste, both organic and inorganic, within the Subak communities in Penebel District exhibited a range of informal practices. Table 7 shows the management of domestic waste in the Subak areas in Penebel District. The survey revealed that 41.10% of the system, i.e., 16 Subaks reported disposing of household waste directly into drainage or irrigation channels. These included Subak Bedugul in Wangaya Gede Village, Sangketa in Sangketa Village, Piling in Mangesta Village, Jegu in Jegu Village, Penebel and Aya Sunantaya in Penebel Village, Rum, Merta, and Srinadi in Senganan Village, Aya Babahan in Babahan Village, Rejasa and Srigumana in Rejasa Village, Penatahan in Penatahan Village, Cepik and Tajen in Tajen Village, and Sigaran in Jegu Village. This practice posed significant ecological risks such as deterioration of water quality, eutrophication, and long-term soil contamination, as pollutants flew untreated into irrigation systems that were crucial for rice cultivation. This method was often preferred by residents due to its perceived convenience, as waste was believed to be "washed away" by flowing water. However, this practice contributed significantly to the accumulation of waste downstream, clogging of irrigation infrastructure, degradation of water quality by pollutants, and disruption of the ecological balance of rice fields.

Table 7. Domestic waste management in the Subak areas in Penebel District

Categories	The Subak (Village)	Total Number of the Subak	Percentage (%)
Waste pits	Tingkih Kerep (Tingkihkerep), Puakan (Tengkudak), Keloncing (Wangaya Gede), Caguh Tempek Ngis (Jegu), Anyar Sangketa (Sangketan), Puring (Sangketan), Petung (Buruan), Tegallinggah (Tegal Linggah), Kebon (Biaung), Tengkudak (Tengkudak), Benana (Jegu), Pancoran Sari (Tengkudak), Buruan (Buruan), Riang (Riang Gede)	14	36.84%
River/Irrigation untreated	Bedugul (Wongaya Gede), Sangketan (Sangketan), Piling (Mangesta), Jegu (Jegu), Penebel (Penebel), Rum (Senganan), Aya Babahan (Babahan), Rejasa (Rejasa), Srigumana (Rejasa), Aya Sunantaya (Penebel), Penatahan (Penatahan), Cepik (Tajen), Sigaran (Jegu), Merta (Senganan), Srinadi (Senganan), Tajen (Tajen)	16	42.11%
Compost/Manure fertilizer	Serason (Pitra), Wangaye Betan (Mangesta), Aya Pemanis (Biaung), Pesagi (Pesagi), Piak (Bengkel), Jatiluwih (Jatiluwih), Abian Sawan (Pemanis Kelod), Kedampal (Mangesta)	8	21.05%
Total		38	100%

Fourteen Subaks, 36.84% of the residents, reported burying their waste in pits typically located behind homes. These included Subak Tingkih Kerep in Tingkihkerep Village, Subak Puakan in Tengkudak Village, Subak Keloncing in Wangaya Gede Village, Subak Caguh Tempek Ngis in Jegu Village, Subak Anyar Sangketa and Subak Puring in Sangketa Village, Subak Petung and Subak Buruan in Buruan Village, Subak Tegallinggah in Tegal Linggah Village, Subak Kebon in Biaung Village, Subak Tengkudak and Subak Pancoran Sari in Tengkudak Village, Subak Benana in Jegu Village, and Subak Riang in Riang Gede Village. While this approach prevented direct contamination of irrigation channels, it carried the risk of leachate seepage into groundwater if not managed properly. These waste pits were often used to accumulate both organic and inorganic waste, eventually burned to reduce volume. Although this method might temporarily remove visible waste from the living environment, it raised serious concerns about air pollution and incomplete combustion of plastics and synthetic materials which could release harmful toxins.

Only eight Subaks, 21.06% of the residents reported efforts to compost organic waste by converting food scraps, leaves, and animal manure into fertilizer for home gardens or rice fields. These Subaks included Subak Serason in Pitra Village, Subak Wangaye Betan and Subak Kedampal in Mangeseta Village, Subak Aya Pemanis in Biaung Village, Subak Pesagi in Pesagi Village, Subak Piak in Bengkel Village, Subak Jatiluwih in Jatiluwih Village, and Subak Abian Sawan in Pemanis Kelod Village. These communities represented a growing segment that recognized the value of organic materials as agricultural input. However, this practice remained limited and often coexisted with less sustainable methods for handling inorganic waste, which was frequently burned or discarded without segregation. Figure 9 identifies spatial distribution of irrigation waste management and domestic waste management across the Subak areas in Penebel District.

Several Subak units in Penebel District demonstrated exemplary waste management practices and maintained relatively clean irrigation water. These include Subak Buruan (Buruan Village), Subak Kebon (Biaung Village), Subak Tingkih Kerep (Tingkihkerep Village), Subak Keloncing (Wangaya Gede Village), Subak Caguh Tempek Ngis (Jegu Village), Subak Puakan (Tengkudak Village), Subak Anyar Sangketan (Sangketan Village), Subak Pancoran Sari (Tengkudak Village), Subak Puring (Sangketan Village), Subak Riang (Riang Gede Village), Subak Tengkudak (Tengkudak Village), and Subak Benana (Jegu Village).

These Subaks were observed to implement better waste segregation practices and minimize direct disposal of household or livestock waste into irrigation canals. Organic waste in these areas was frequently composted or reused in agricultural plots while inorganic waste, though present, was managed with greater care to prevent accumulation in water bodies. In addition, these Subaks tended to have stronger local regulations such as Awig-Awig or more active community involvement in regular waste cleanup and irrigation maintenance.

As a result, irrigation water in these areas was reported to be "clean" and suitable for agricultural use, despite minor suspended solids such as silt or biodegradable debris. These Subak units could serve as references for best practices in integrated organic waste management and preservation of traditional irrigation system in the agroecological landscape of Bali.

Informal and unregulated practices of waste disposal, such as dumping into irrigation channels and burning waste in backyard pits reflect limited infrastructure and low environmental awareness. The prevalence of domestic, livestock, and small-scale industrial waste demands a comprehensive approach combining community education, behavioral change, and localized regulation. Without proper intervention, the waste streams pose a serious threat to the sustainability of the Subak-managed agricultural systems and the integrity of traditional water resources essential for organic rice farming.

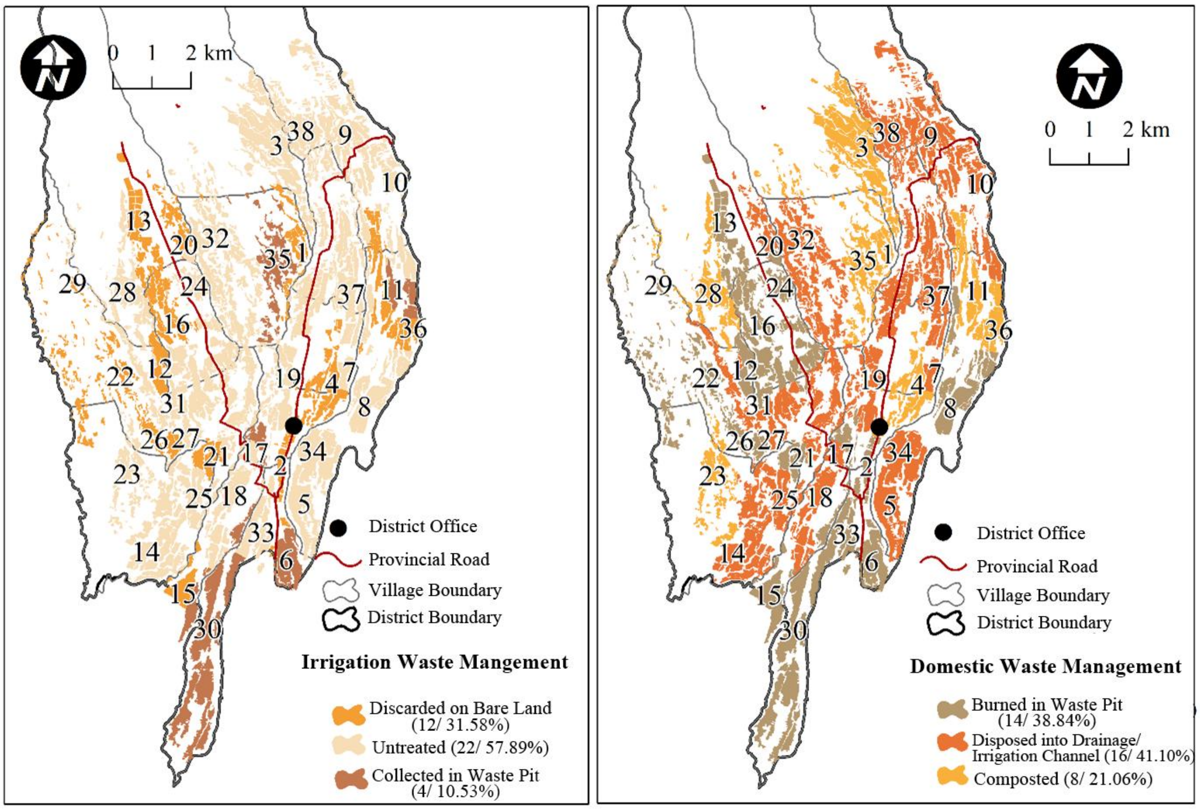


Figure 9. Spatial distribution of irrigation waste management (left) and domestic waste management (right)

To improve environmental condition and support sustainable agriculture, the Subak communities require differentiated and context-sensitive waste management strategies. Organic waste should be composted or processed into biofertilizer, while inorganic waste necessitates structured collection and recycling mechanisms. Institutional support is needed to build infrastructure, promote source segregation, and prevent waste disposal into water bodies. Revitalizing the customary law, Awig-Awig, in combination with modern environmental education and policy incentives, could help bridge local practices with ecological goals. In Bali, Awig-Awig, the customary law governing community and natural resource management plays a crucial role in regulating agricultural practices, water distribution, and environmental stewardship within the traditional Subak irrigation systems. The norms generated by Awig-Awig are not merely rules but also the embodiment of socio-cultural values to guarantee both ecological balance and social cohesion (Zen et al., 2024).

Community-based programs could strengthen Awig-Awig by facilitating participatory mapping, local environmental monitoring, and inclusive decision-making platforms that engage multiple stakeholders, including youth and marginalized groups. For example, waste mapping initiatives within the Subak territories could integrate the provisions of Awig-Awig on environmental cleanliness, thereby linking traditional norms with modern practices of sustainability (Cochrane et al., 2014). Capacity-building workshops and inter-generational dialogues could ensure that Awig-Awig is transmitted effectively while adapting to new environmental challenges.

From the political perspective, local governments could institutionalize Awig-Awig through formal recognition of regional regulations or incorporation of the customary law into the frameworks of spatial planning and agricultural management. Such formalization provides legal reinforcement and potential funding support for Awig-Awig-based environmental programs (Suwitra et al., 2021; Yulianingsih & Hastuti, 2019). Additionally, the integration of national programs such as Indonesia's *Desa Adat* (Customary Village) empowerment initiatives helps scale community-led governance while preserving cultural identity.

Ultimately, revitalizing Awig-Awig requires a hybrid approach that respects customary authority while enhancing its adaptability through modern community development and policy mechanisms. This dual strategy ensures that traditional regulations remain both culturally relevant and operationally effective in addressing contemporary environmental challenges. These integrated efforts are essential to protect water quality, restore ecological function, and align the Subak communities with the principles of organic and sustainable farming.

Research by Huyen & Lai (2019) in the Mekong Delta of Vietnam demonstrated that improper domestic waste disposal into canals adversely affected water quality and increased maintenance costs for irrigation networks; this was a situation comparable to the condition observed in Penebel District. Similarly, Nabuurs et al. (2023) reported that contamination from livestock waste in irrigation channels was closely linked to the absence of waste segregation and enforcement of local regulations. These findings were consistent with the results in the present study, which showed that both domestic and livestock activities notably contributed to the waste in irrigation water.

Previous studies also emphasized the interplay between the types of waste and management practices. Lackner & Besharati (2025) found that compared to single-category waste, mixed waste, including both organic and inorganic, posed greater challenges for irrigation maintenance as it required both physical removal and chemical treatment. This aligned with the current classification of waste types into organic, inorganic, and mixed to ensure a more targeted approach in waste management strategies. Furthermore, Rahmi & Setiawan (2020), focusing on the Subak system in Bali, highlighted that community-based waste management programs could substantially improve the quality of irrigation water when supported by local regulations and regular monitoring.

Studies on participatory mapping approach as conducted by Denwood et al. (2022), have demonstrated the importance of integrating local knowledge into identifying waste hotspots and prioritizing areas for intervention. The similarity found in their methodology reinforced the validity of the participatory approach used in the current study in assessing the sources of waste and management practices within the Subak irrigation network. By drawing on these relevant studies, the discussion was placed within a broader regional and methodological context, hence strengthening the argument for community-led and location-specific waste management solutions.

With the participatory approach, this study focused on assessing the significance levels of plastic waste in the Subak irrigation system by the local respondents. The assessment was carried out with classification based on community perceptions and field observations, covering the condition of irrigation water as well as the quality of irrigation infrastructure. In addition, this study distinguished between the parameters and sources of waste, both organic and inorganic, based on the domestic, livestock, and industrial origins. By incorporating diverse parameters, the study contributed to recommending solutions for the irrigation waste management to be implemented independently by the Subak members.

4. Conclusions

The findings from the assessment of irrigation and waste in the Subak areas of Penebel District underscored the critical challenges facing traditional irrigation water systems in Bali. The quality of irrigation water is generally compromised by the presence of both organic and inorganic waste originating from domestic, livestock, industrial, and upstream sources. While a portion of the Subaks still receives irrigation water deemed "clean" for agricultural use, the prevalence of plastic waste, livestock manure, and chemical residues threatens the ecological balance of the Subak-managed landscapes. Furthermore, the structural degradation of irrigation infrastructure due to financial constraints at both government and community levels, hampers the efficiency of water delivery and exacerbates environmental decline.

The lack of structured and institutionalized waste management systems has led to the widespread use of informal disposal practices, including direct dumping into irrigation channels, burning waste in open pits, and unsegregated waste burial. These methods undermine water quality, soil health, and air quality, posing long-term risks to sustainable agriculture and food security. To align the Subak systems with organic farming principles, there is an urgent need for integrated and community-based waste management strategies that promote composting, discourage pollution of water bodies, and revitalize customary norms like Awig-Awig for environmental stewardship. Institutional support through education, infrastructure, and policy incentives will be the key to transforming the Subak landscapes into models of sustainability and culturally rooted agroecological resilience.

Author Contributions

Conceptualization, I.K.S. and P.P.K.W.; methodology, I.K.S. and P.P.K.W.; software, P.P.K.W.; validation, I.K.S., P.P.K.W., A.A.A.W.S.D., and N.M.A.K.D.; formal analysis, I.K.S., P.P.K.W., A.A.A.W.S.D., and N.M.A.K.D.; investigation, P.P.K.W.; resources, I.K.S.; data curation, A.A.A.W.S.D., and N.M.A.K.D.; writing—original draft preparation, I.K.S and P.P.K.W.; writing—review and editing, A.A.A.W.S.D., and N.M.A.K.D.; visualization, P.P.K.W.; supervision, I.K.S.; project administration, A.A.A.W.S.D., and N.M.A.K.D.; funding acquisition, I.K.S. All authors have read and agreed to the published version of the manuscript.

Funding

This work is funded by the Budget Implementation List (DIPA) of Udayana University for the 2024 Fiscal Year (Grant No.: SP DIPA 023.17.2.677526/2024).

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Acknowledgements

Authors thank the Agriculture Agency of Tabanan Regency for the support.

Conflicts of Interest

The authors declare no conflict of interest.

References

Ardana, P. D. H., Suparwata, D. O., Sudrajat, A., Chatun, S., & Harsono, I. (2024). The role of Bali's traditional subak farming system in the preservation of natural and cultural resources. *West Sci. Nat. Technol., 2*(1), 31-38.

Astarini, I. A., Pharmawati, M., Defiani, M. R., Siddique, K. H. M. (2020). Development of local rice on the Tabanan Regency of Bali. In: M. Blakeney & K. Siddique (Eds), *Local Knowledge, Intellectual Property and Agricultural Innovation* (pp. 153–171). Springer, Singapore. https://doi.org/10.1007/978-981-15-4611-2_8.

Bazen, A., Barg, F. K., & Takeshita, J. (2021). Research techniques made simple: An introduction to qualitative research. *J. Investig. Dermatol.*, *141*(2), 241–247. https://doi.org/10.1016/j.jid.2020.11.029.

BPS-Statistics Indonesia Tabanan Regency. (2024). *Tabanan Regency in Figures 2024*. https://tabanankab.bps.go.id/en/publication/2024/02/28/42fd67af98f38edf826c46d0/kabupaten-tabanan-dalam-angka-2024.html

Cochrane, L., Corbett, J., & Keller, P. (2014). *Impact of community-based and participatory mapping*. Institute for Studies and Innovation in Community–University Engagement, University of Victoria, Canada. https://doi.org/10.13140/RG.2.1.4522.5360.

Cui, Y., Gjerde, M., & Marques, B. (2024). Mapping and assessing effective participatory planning processes for urban green spaces in Aotearoa New Zealand's diverse communities. *Land*, *13*(9), 1412. https://doi.org/10.3390/land13091412.

Delina, L. L., Fuerzas, I., Dharmiasih, W., Dulay, M. J., & Salamanca, A. (2024). Are capital assets under pressure? The state of and challenges to indigenous rice farming in the cultural ricescapes of Indonesia and the Philippines. *J. Rural Stud.*, *106*, 103235. https://doi.org/10.1016/j.jrurstud.2024.103235.

Denwood, T., Huck, J. J., & Lindley, S. (2022). Participatory mapping: A systematic review and open science framework for future research. *Ann. Am. Assoc. Geogr.*, *112*(8), 2324–2343. https://doi.org/10.1080/24694452.2022.2065964.

Djelantik, A. A. A. W. S., Mahendra, I. M. S., Windia, I. W., & Sudarma, I. M. (2023). The impact of rice field functional shifts on sustainability and greenhouse gas emissions in Tabanan Regency, Bali, Indonesia. *Int. J. Des. Nat. Ecodyn.*, *18*(3), 685–692. https://doi.org/10.18280/ijdne.180321.

Gava, O., Ardakani, Z., Delalic, A., & Monaco, S. (2024). Environmental impacts of rice intensification using high-yielding varieties: Evidence from Mazandaran, Iran. *Sustainability*, *16*(6), 2563. https://doi.org/10.3390/su16062563.

Huyen, D. T. T. & Lai, T. D. (2019). Assessment of wastewater management in Mekong River Delta region. *J. Sci. Technol. Civ. Eng. Huce*, *13*(2), 82–91. https://doi.org/10.31814/stce.nuce2019-13(2)-08.

Ivancov, C. (2025). *Community, governance, and UNESCO: The contested management of Bali's Subak world heritage site*. B-TU WHS/Cultural Landscapes. https://doi.org/10.13140/RG.2.2.18162.82882.

Lackner, M. & Besharati, M. (2025). Agricultural waste: Challenges and solutions, a review. *Waste*, *3*(2), 18. https://doi.org/10.3390/waste3020018.

Mali, M., Kammara, M., Kadapala, A., Kumar, V., Lakshmi, P., Karmakar, S., Lakra, D., Kiran, R., Akanand, & Chandrakar, G. (2023). The future of rice farming: A review of natural and eco-friendly practices. *Int. J. Environ. Climate Change*, *13*(11), 4240–4249. https://doi.org/10.9734/ijecc/2023/v13i113604.

Nabuurs, G. J., Mrabet, R., Abu Hatab, A., Bustamante, M., Clark, H., Havlík, P., House, J., Mbow, M., Ninan, K. N., Popp, A., et al. (2023). Agriculture, forestry and other land uses (AFOLU). In *Climate Change 2022–Mitigation of Climate Change* (pp. 747–860). Cambridge University Press. https://doi.org/10.1017/9781009157926.009.

Norken, I. N. (2019). Efforts to preserve the sustainability of Subak irrigation system in Denpasar City, Bali Province, Indonesia. *MATEC Web Conf.*, *276*, 04002. https://doi.org/10.1051/matecconf/201927604002.

Parsons, M., Taylor, L., & Crease, R. (2021). Indigenous environmental justice within marine ecosystems: A systematic review of the literature on indigenous peoples' involvement in marine governance and management. *Sustainability*, *13*(8), 4217. https://doi.org/10.3390/su13084217.

Prastyadewi, M. I., Parwita, G. B. S., & Pramandari, P. Y. (2023). Utilization of the Subak Jatiluwih landscape as a tourism object: Tourist perceptions and the impact on village income. *J. Penelit. Ekon. Bisnis*, *8*(1), 48–56. https://doi.org/10.33633/jpeb.v8i1.7917.

Prastyadewi, M. I., Susilowati, I., & Iskandar, D. D. (2020). Preserving the existence of Subak in Bali: The role of social, cultural, and economic agencies. *Economia Agro-alimentare/Food Econ.*, *22*(3), 7. https://doi.org/10.3280/ecag3-2020oa11045.

Rahmi, D. H. & Setiawan, B. (2020). Pressures on the Balinese world cultural landscape heritage: The case of Jatiluwih Subak village. *IOP Conf. Ser.: Earth Environ. Sci.*, *501*, 012032. https://doi.org/10.1088/1755-1315/501/1/012032.

Robinson, G. M. (2024). Global sustainable agriculture and land management systems. *Geogr. Sustain.*, *5*(4): 637–646. https://doi.org/10.1016/j.geosus.2024.09.001.

Sardiana, I. K. & Wiguna, P. P. K. (2023). Evaluating spatial data infrastructure for Subak management in Tabanan Regency, Bali, Indonesia. *Int. J. Des. Nature Ecodyn.*, *18*(5), 1033–1043. https://doi.org/10.18280/ijdne.180503.

Shiotsu, F., Sakagami, N., Asagi, N., Suprapta, D. N., Agustiani, N., Nitta, Y., & Komatsuzaki, M. (2015). Initiation and dissemination of organic rice cultivation in Bali, Indonesia. *Sustainability*, *7*(5), 5171–5181. https://doi.org/10.3390/su7055171.

Si, R., Pan, S., Yuan, Y., Lu, Q., & Zhang, S. (2019). Assessing the impact of environmental regulation on livestock manure waste recycling: Empirical evidence from households in China. *Sustainability*, *11*(20), 5737. https://doi.org/10.3390/su11205737.

Susilawati, N. K. S., Susrusa, K. B., & Sudarma, I. M. (2025). Sustainability analysis of black rice farming in Penebel District, Tabanan Regency, Bali Province. *Int. J. Econ. Perspect.*, *19*(7), 195–209.

Suwitra, I. M., Astara, I. W. W., Wijaya, I. K. K. A., & Arthanaya, I. W. (2021). Strengthening Balinese customary laws through Awig-Awig writing in Pekutatan Negara traditional village. In *Proceedings of the First International Seminar Social Science, Humanities and Education (ISSHE 2020), 25 November 2020, Kendari, Southeast Sulawesi, Indonesia* (pp. 40–45). http://doi.org/10.4108/eai.25-11-2020.2306661.

Trigunasih, N. M. & Saifulloh, M. (2022). The investigating water infiltration conditions caused by annual urban flooding using integrated remote sensing and geographic information systems. *J. Environ. Manag. Tour.*, *13*(5), 1467–1480. https://doi.org/10.14505/jemt.v13.5(61).22.

Yasmita, I. G. A. L. (2025). Realizing sustainable agriculture in Bali: How land-use conversion impacts the future of food security and local culture in Tabanan. *J. Widya Publika*, *13*(1), 31–48. https://doi.org/10.70358/widyapublika.v13i1.1375.

Yulandari, A., Sudarma, I. M., & Arisena, G. M. K. (2021). Functional change of agricultural land in Tabanan Regency, Bali (Case study in Subak Jadi, Kediri District). *Agriecobis J. Agric. Socioeconom. Bus.*, *4*(1), 13–21. https://doi.org/10.22219/agriecobis.v4i1.12651.

Yulianingsih, W. & Hastuti, P. (2019). Customary regulations for Awig-Awig as a depending the state-based environmental conservation effort in the village of Pakraman, Bai Province. In *Nusantara Science and Technology Proceedings* (pp. 343–353). https://doi.org/10.11594/nstp.2019.0246.

Zen, I. S., Surata, S. P. K., Titisari, P. W., Rahman, S. A. A. & Zen, S. (2024). Sustaining Subak, the Balinese traditional ecological knowledge in the contemporary context of Bali. *IOP Conf. Ser.: Earth Environ. Sci. 1306*, 012034. https://doi.org/10.1088/1755-1315/1306/1/012034.