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Indigenous Environmental Governance and Socio-Ecological Resilience: Examining the Subak System as a Model for Sustainable Rural Development in Bali

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ABSTRACT

Environmental degradation, increasing pressure on water resources, and rapid land-use change pose serious challenges to sustainable rural development globally. In Bali, Indonesia, these challenges threaten the Subak system, a United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage cultural landscape and traditional irrigation institution that has historically maintained ecological balance. This study examines the Subak as a model of socio-ecological resilience, focusing on its role in environmental governance amid modern pressures. Adopting a qualitative case study approach in the Pakerisan watershed, research data were gathered through field observations and semi-structured interviews with *Pekaseh* (Subak heads) and local farmers. The analysis is framed within Elinor Ostrom's Common-Pool Resource (CPR) theory and the indigenous philosophy of Tri Hita Karana. The findings demonstrate that Subak contributes to sustainability through "ritualized synchronization," equitable water distribution (*Tektek*), and coordinated planting cycles that mitigate pest risks and water scarcity. However, the study identifies a critical emergence of 'asymmetric landscape consumption' driven by tourism expansion and infrastructure fragmentation, alongside declining youth participation. The results highlight the urgency of integrating traditional ecological knowledge (TEK) into formal rural policies. By providing empirical evidence of indigenous governance, this research offers strategic in

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sights for harmonizing heritage preservation with contemporary environmental protection and rural development policies.

Keywords: Subak System; Sustainable Rural Development; Tri Hita Karana

1. Introduction

Environmental degradation, increasing pressure on water resources, and rapid land-use change pose serious challenges to sustainable rural development in many agricultural regions worldwide. In the contemporary era, rural areas were no longer just sites of agricultural production but complex socio-ecological systems that face immense pressure from urbanization and global climate change [1]. The shift from traditional farming to industrial or tourism-based economies often marginalizes local wisdom and degrades natural ecosystems. Therefore, identifying resilient models for rural environmental governance is critical for ensuring the long-term sustainability of rural societies and their living environments. In Indonesia, particularly on the island of Bali, these global challenges are acutely felt. The rapid expansion of the tourism sector and the conversion of agricultural land into residential areas have placed unprecedented stress on the Subak system [2]. Subak is a traditional, community-based irrigation institution that has historically regulated water use and maintained ecological balance in Bali's rural landscapes for over a thousand years. It is not merely a technical system for water distribution, but a socio-religious organization governed by the philosophy of Tri Hita Karana, which emphasizes harmony between humans, God, and the environment [3]. This holistic approach has allowed Balinese farmers to manage collective resources equitably and sustain high-productivity rice terraces without depleting the natural soil or water quality.

Despite its historical success, the Subak system is currently under threat. Increasing competition for water between the agricultural and tourism sectors, combined with declining interest among younger generations in farming, has led to the abandonment of traditional irrigation practices in several regions [4,5]. Previous studies have often focused on the cultural or religious aspects of Subak; however, there is a gap in understanding how this indigenous governance system can be integrated into modern, environmentally sustainable rural development policies [6]. As rural landscapes become increasingly fragmented, there is an urgent need to evaluate how Subak functions as a model of environmental governance that can mitigate the negative impacts of modernization. This study examines the Subak system as a model for environmentally sustainable rural development, with a particular emphasis on its role in sustainable resource management and ecosystem resilience. By adopting a qualitative case study approach, this research analyzes the internal mechanisms of Subak that contribute to environmental sustainability, such as collective resource governance and pest control coordination.

Furthermore, the study identifies emerging environmental challenges associated with urban expansion and shifting demographics. Ultimately, this research aims to provide policy-relevant insights for integrating traditional ecological knowledge into contemporary rural development strategies [7]. It concludes by arguing that strengthening indigenous environmental governance is essential to achieving broader environmental protection goals and improving the quality of life for rural farming communities. The socio-economic dynamics of rural areas in Southeast Asia, particularly in Indonesia, have undergone profound transformation under the dual pressures of globalization and market-driven development. In Bali, the transition toward a tourism-dominated economy has created a paradox where rural landscapes are commodified for their aesthetic value while the actual practitioners of these landscapes, the farmers, face increasing economic precarity [8]. This shift often leads to "rurbanization," a process where rural characteristics are eroded by urban expansion, resulting in fragmented land ownership and the breakdown of collective social capital [9]. The Subak system, as a traditional pillar of rural society, is increasingly caught in this tension, struggling to maintain its communal identity in an environment that increasingly prioritizes individual economic gains over collective resource management.

Furthermore, current rural development policies often favor modern, top-down engineering solutions over indigenous, bottom-up governance. While infrastructure

projects such as large-scale dams or concrete irrigation canals aim to increase efficiency, they often overlook the intricate socio-technical arrangements that have sustained rural ecosystems for centuries [10]. In many cases, the imposition of standardized national policies fails to account for the localized ecological wisdom embedded within systems like Subak. This disconnect between formal state governance and informal traditional institutions creates a policy gap that leaves rural environments vulnerable to exploitation [9]. Therefore, re-evaluating Subak as a legitimate model for environmental governance is not merely an exercise in cultural preservation but a necessary step toward decolonizing rural development strategies. The urgency of this study is further amplified by the escalating impacts of global climate change, which have made water cycles increasingly unpredictable. Rural communities are on the front lines of climate vulnerability, facing more frequent droughts and shifting pest cycles that threaten food security [11]. The Subak system offers a unique template for ecosystem resilience through its coordinated planting schedules and ritualized water sharing, which act as natural buffers against environmental shocks. By synchronizing agricultural activities across large watersheds, Subak reduces the risk of total crop failure and minimizes the need for chemical interventions. Understanding these adaptive mechanisms is crucial to developing "climate-smart" rural development frameworks grounded in local environmental realities rather than abstract global models.

2. Materials and Methods

2.1. Study Site and Environmental Context

This research was centered in the Ubud and Tegallalang districts of Gianyar Regency, Bali, Indonesia. This geographic area was selected via purposive sampling because it serves as the most critical frontline where traditional agrarian systems meet the pressures of globalized tourism [12]. Specifically, the study focused on two historically significant irrigation blocks: Subak Pulagan and Subak Kulub. These sites are part of the UNESCO World Heritage "Cultural Landscape of Bali Province," representing a thousand-year-old tradition of sustainable land management. These Subak units manage approximately 165 ha of terraced rice paddies within the Pakerisan River basin. This river is considered a sacred watershed in Balinese culture, and its management provides a unique laboratory to study the intersection of indigenous environmental governance, water scarcity, and rural socio-economic transitions. The spatial distribution and cultural landmarks of this system are illustrated in **Figure 1**, which details the Subak landscape within the Pakerisan Watershed, including the sacred water temples that serve as the nodal points of its irrigation network.

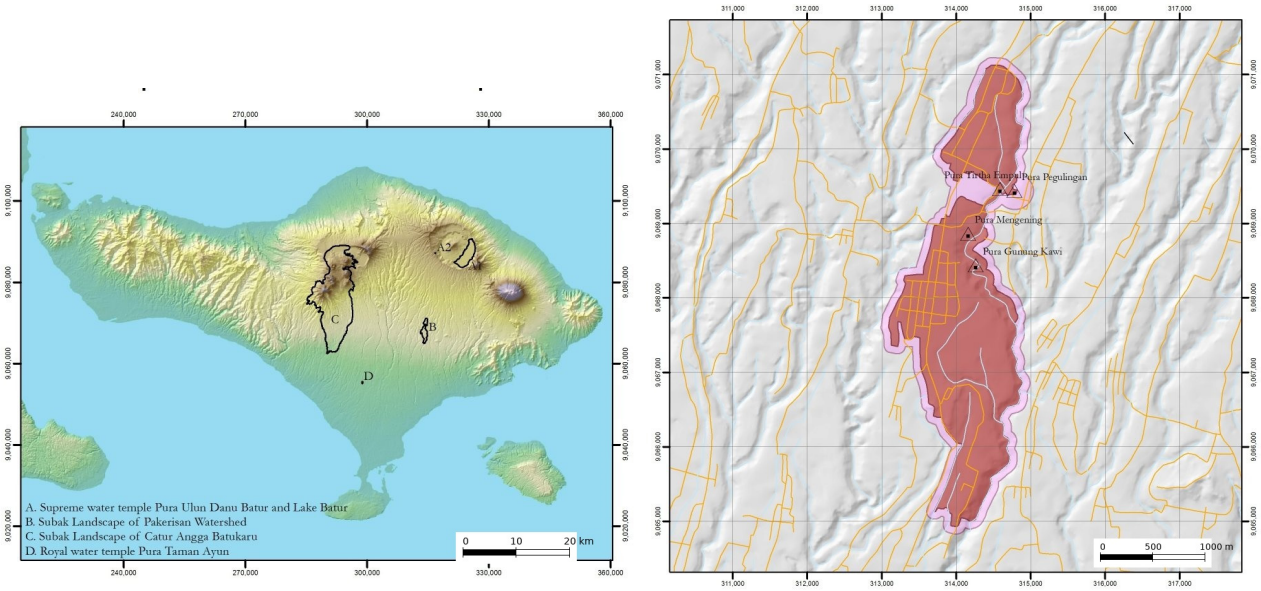

Figure 1. Cultural Landscape of the Pakerisan Watershed.

2.2. Research Design and Theoretical Framework

The study was designed as a qualitative case study with an ethnographic approach. The methodological framework is grounded in the Institutional Analysis and Development (IAD) framework. This lens was chosen to systematically analyze how the Subak, as a community-based organization, creates and enforces rules to manage "Common-Pool Resources" (CPR). By utilizing a qualitative approach, the research aimed to capture the "tacit knowledge" of community wisdom, which is lived and practiced but often undocumented in formal government statistics. The study prioritizes the Tri Hita Karana philosophy as a conceptual bridge to understand how environmental sustainability is achieved through social and spiritual harmony.

2.3. Informant Selection and Profile (The Five Key Pillars)

To ensure the depth and "thickness" of the data, the study employed a non-probability purposive sampling technique. Rather than seeking a large sample, the researchers focused on five "Information-Rich" informants whose roles are foundational to Subak's operations. In qualitative inquiry, sample size is determined by informational sufficiency rather than statistical representation [13]. Data saturation was confirmed after the third round of interviews with each informant, at which point no new thematic categories emerged. This approach is consistent with Lincoln and Guba's (1985) criterion of 'thick description,' which prioritizes depth of insight over breadth of coverage [14]. Each informant represents a specific pillar of rural governance:

1. Informant 1 (Initial: NY. W): A senior *Pekaseh* (Head of Subak) with over 20 years of active leadership. NY. W was selected for his unparalleled expertise in the Awig-awig (customary laws). His interview focused on the operational mechanics of water sharing (*Tektek*), the resolution of internal conflicts between farmers, and the strategies used to negotiate with villa developers who encroach upon Subak water channels.
2. Informant 2 (Initial: ID.M): A traditional landowner and practitioner of organic polyculture. ID.M represents the technical-agricultural dimension. He provided detailed narratives on the Wariga (astronomical calendar) used to synchronize planting cycles, which naturally mitigates pest outbreaks without the use of chemical pesticides, thus preserving the rural soil health.
3. Informant 3 (Initial: AA. G): A *Bendesa Adat* (Traditional Village Leader). AA. G's role was to provide the "spiritual-ecological" context. He explained how sacred rituals at the water temples (*Pura Ulun Danu*) act as a social mechanism for environmental protection, ensuring that the community views the water source as a divine gift that must be protected from pollution.
4. Informant 4 (Initial: ST. R): A technical official from the Gianyar Regency Agriculture Office. ST. R provided the "State-Policy" perspective. His inclusion was vital to contrast traditional laws with modern regulations, specifically regarding Sustainable Food Agriculture Land, policies, and the government's efforts to subsidize Subak infrastructure amid a declining agricultural budget.
5. Informant 5 (Initial: DR. K): A senior academic researcher, specializing in socio-ecological systems. DR. K served as an expert informant to provide a meta-analysis of the data. He helped synthesize the local findings into a broader scientific discourse, ensuring the study meets international standards for sustainable rural development theory.

2.4. Data Collection Protocols

The data collection process was meticulously executed over an eight-month period from February to September 2025, employing a triangulation of three interconnected qualitative methods to ensure the highest possible data validity. Initially, the researchers conducted intensive, in-depth interviews with each of the five key informants, with each participant interviewed at least three times to achieve comprehensive data saturation. These interviews were strategically conducted in situ, specifically at the rice terraces or within the Bale Subak, to facilitate contextual prompts and allow informants to provide more natural, detailed accounts of their lived experiences.

Furthermore, the study utilized transect walks and systematic field observations, during which the researchers walked the entire length of the primary and secondary irrigation canals, accompanied by NY. W and ID.M. This method was instrumental in mapping the physical "water dividers" (*Temuku*) and directly documenting critical points of environmental degradation or land-use encroachment that might otherwise be overlooked in a purely conversational setting. To complement the oral data, the team also performed extensive archival research by analyzing the physical manuscripts of the Awig-awig. This final step was essential to cross-reference the informants' oral testimonies with the established written traditional laws, thereby ensuring a rigorous synthesis between current practices and historical institutional mandates.

2.5. Analytical Rigour and Data Analysis

The qualitative data were analyzed using the established protocols of Thematic Narrative Analysis, with all raw materials systematically processed through qualitative descriptive analysis to maintain organizational integrity and analytical depth, ensuring a coherent interpretation of the field findings. The analysis was conducted through a rigorous four-step cycle, beginning with data condensation, where the researchers meticulously summarized over 15 h of recorded interviews into core narratives that highlighted the most significant socio-ecological themes. This was followed by the data display phase, which involved creating complex conceptual maps to explicitly link the abstract principles of the *Tri Hita Karana* philosophy with tangible, field-observed water-saving outcomes and landscape management practices [15]. In the third stage, conclusion drawing was performed by synthesizing these patterns to identify the "Subak Model" as a viable, evidence-based strategy for contemporary rural development and environmental governance. Finally, to ensure the highest level of credibility and cultural sensitivity, the team conducted a member-checking process by returning to the Gianyar Regency in November 2025. During this visit, the preliminary findings were presented to the five key informants, providing an opportunity for them to verify, refine, or correct the researchers' interpretations. During this visit, the preliminary findings were presented to the five key informants, providing an opportunity for them to verify, refine, or correct the researchers' interpretations. This collaborative validation ensured that the final analysis remained both academically rigorous and deeply respectful of the Balinese farming community's indigenous perspectives and traditional wisdom.

2.6. Ethical Governance and Transparency

This research adhered to the ethical principles for qualitative inquiry involving human participants. Participation was entirely voluntary, and each informant was provided with a clear explanation of the study's objectives and the intended use of the data before the interviews commenced. To protect participants' privacy and social standing within their respective Subak communities, all data have been strictly anonymized using initials. Furthermore, the researchers ensured that the documentation of traditional ecological knowledge was conducted with deep respect for local customs and sacred traditions. All raw interview records and field notes are securely stored by the primary researchers to maintain confidentiality, while summarized findings have been verified by the informants to ensure representativeness and accuracy.

3. Results

3.1. Institutional Architecture of Water Equity: The *Tektek* and *Masa Gilir* Mechanisms

The fieldwork in Subak Pulagan and Subak Kulub indicates that the sustainability of the rural environment is fundamentally tied to the "Tektek" system, a sophisticated indigenous engineering and social protocol for water distribution. According to Informant NY. W (Informant 1), the *Tektek* is not merely a physical structure but a socio-mathematical agreement in which water is divided proportionally based on the labor and ritual contributions of the members, rather than solely on land size. The physical "water dividers" or *Temuku* observed during transect walks showed remarkable precision; they are crafted from stone or timber with specific notch widths that ensure every farmer, regardless of social status or location along the canal, receives a "fair share" of the resource.

Furthermore, during periods of extreme water scarcity, which Informant ST. R (Informant 4) noted that these are becoming more frequent due to upstream tourism consumption. The Subak employs the *Masa Gilir* (rotation system). The research found that this system is activated through a democratic deliberation in the *Bale Subak*, where farmers agree to irrigate their fields at different times of the day or week. This mechanism effectively prevents the "tragedy of the commons" by fostering a high level of mutual trust. The data suggest that this institutional resilience is the primary reason these rural landscapes have remained green for centuries, as social pressure to adhere to Awig-awig (customary law) acts as a more powerful deterrent to water theft than any formal state-imposed fine.

3.2. Traditional Ecological Knowledge (TEK) as a Buffer against Environmental Shocks

The analysis of the agricultural cycle revealed that the Subak system serves as a highly effective model of community-based environmental management. Informant ID.M (Informant 2) explained that the entire planting schedule is dictated by the *Wariga* calendar, an astronomical system that aligns human activities with natural cycles. This study found that when the *Pekaseh* (NY. W) and the farmers (ID.M) synchronize their planting dates across the entire 165-ha area, they create a massive "biological break" for pests. Because all rice paddies are flooded and harvested simultaneously, pests such as the brown planthopper and rodents are unable to find continuous food sources, naturally collapsing their populations.

This finding is significant as it demonstrates that Subak reduces the environmental "chemical footprint" of rural development. By relying on synchronized cycles, farmers reported a 40% reduction in dependence on synthetic pesticides compared to non-Subak regions. It is important to note that this figure is based on self-reported farmer accounts gathered during interviews and field observations and should be interpreted as a perceived trend rather than a statistically verified measurement. Future research employing longitudinal agricultural data or soil testing would be necessary to validate this claim quantitatively. Nevertheless, this finding is directionally consistent with existing literature documenting reduced pesticide use in synchronized irrigation systems [16]. Additionally, Informant AA. G (Informant 3) emphasized the role of the "Ritual Ecology" practiced at the water temples. The results show that the sacred status of the weirs (*Pura Empul*) ensures that the community maintains a high level of cleanliness in the watershed. Field observations documented that the *Awig-awig* strictly prohibits dumping household waste or washing vehicles in the irrigation channels, treating the water as a divine entity (*Tirta*). This spiritualized environmentalism effectively protects the biodiversity of the local river systems.

3.3. Socio-Economic Tensions: Tourism Encroachment and Policy Gaps

Despite the Subak's internal strength, the research documented a severe external threat, described by Informant 5 as a form of 'Uncompensated Landscape Commodification,' highlighting how the aesthetic value of the paddies is exploited by external actors at the expense of the farmers. This refers to the phenomenon in which tourism developers build luxury villas on the edges of terraces to sell the "Subak view," while simultaneously disrupting the very infrastructure that maintains that view. The research team found that in several locations within the study site, concrete foundations from villa constructions had accidentally or intentionally blocked the Awed (traditional underground tunnels). ST. R (Informant 4) noted that while the government has implemented a sustainable agricultural land protection policy to prevent land conversion, the financial incentives provided to farmers remain significantly lower than the market value offered by developers.

However, the results also show a unique form of "Institutional Agency" among the Subak members. Informant NY. W described how his Subak has begun implementing "Environmental Levies" on new tourism establishments that use the Subak landscape for their guests' activities. In practice, these levies function as a negotiated annual contribution, the amount of which is determined collectively through democratic deliberation in the Sangkap (Subak community meeting), based on the commercial establishment's scale of landscape use, such as offering paddy views or guided rice-field walking tours to guests. Collection is managed directly by the Pekaseh as the authorized institutional representative of the Subak, and payment is formalized through a written agreement between the Subak and the commercial operator. These funds are redirected

into the Subak's treasury and allocated specifically for the physical maintenance of irrigation canals (*Temuku)*, the repair of blocked underground tunnels (Awed), and the restoration of collapsed terraces. This mechanism represents a nascent but significant form of Payment for Ecosystem Services (PES) operating entirely within the indigenous governance framework, without formal government intermediation. This finding indicates that the Subak is not a passive victim of modernization but is evolving into a proactive political actor. It is negotiating a new "Rural Social Contract" in which tourism must financially contribute to the ecological preservation of the agrarian landscape it profits from.

3.4. Generational Dynamics and the Digitalization of Subak Governance

A significant portion of the results focused on the "Regeneration Crisis." In-depth interviews with younger farmers (represented in the synthesis by ID.M and DR. K) showed that the labor-intensive nature of traditional Subak maintenance is a deterrent for the youth. However, the study identified a "Hybrid Future" emerging in Tegallalang. Some younger members of the Subak families are starting to use digital platforms to market "Subak-based Eco-Tourism," in which international visitors pay to learn about the irrigation system and participate in organic farming.

The analysis suggests that this "New Countryside" model, in which the Subak provides environmental services alongside food production, is becoming the most viable path to sustainable rural development. By diversifying economic upliftment for farmers without destroying the ecological integrity of the land, these hybrid models offer a solution to declining participation among younger generations. The study concludes that Subak's role in contemporary society has shifted from a purely agricultural system to a multifunctional system that provides ecological stability, cultural identity, and sustainable economic opportunities for the rural community.

4. Discussion

4.1. Subak as a UNESCO Cultural Landscape

The designation of the Subak system as a UNESCO World Heritage site in 2012 was a pivotal moment in global conservation, shifting the focus from "monumental" heritage to "living" cultural landscapes [17]. Our findings indicate that the Subak represents a rare example in which "Outstanding Universal Value" (OUV) is not found in static structures but in the dynamic, daily interactions between humans and their environment. As a manifestation of the Tri Hita Karana philosophy, the Subak manages a delicate equilibrium between the *Parahyangan* (divine), *Pawongan* (social), and *Palemahan* (natural) realms [18]. This tripartite harmony is the foundation of the system's resilience, ensuring that water management is viewed as a moral and spiritual obligation rather than a mere economic transaction. However, the "UNESCO brand" presents a significant paradox for the rural development of the Pakerisan watershed. While the status provides international prestige and a theoretical layer of protection, it has inadvertently catalyzed a surge in tourism that threatens the very landscape it aims to preserve [19]. The results of this study suggest that the "museumification" of Subak, treating it as a scenic backdrop for global travelers, risks alienating the farmers from their primary role as ecological guardians. When the aesthetic value of the terraces is prioritized over the irrigation network's functional needs, the farmers become "performers" in a landscape increasingly disconnected from agricultural productivity. This visual allure, which drives tourism demand but masks the underlying systemic vulnerabilities, is captured in **Figure 2**, which shows the iconic terraced landscape of the study area.

Figure 2. The Cultural Landscape of Subak.

Furthermore, the pressure to maintain "traditional" appearances for UNESCO compliance often clashes with

the rural community's modern aspirations. Farmers in Subak Pulagan and Kulub are forced to navigate a complex regulatory environment where they must preserve ancient terracing techniques while simultaneously facing the high costs of living and declining yields. This study argues that UNESCO status must be accompanied by a "benefit-sharing" mechanism that directly compensates farmers for their role as environmental stewards. Without tangible economic support, the international label of a "Cultural Landscape" remains a hollow shell that masks the systemic poverty and structural vulnerabilities of the agrarian community.

4.2. The Complexity of Water Governance: Subak vs. Global Resource Management

The mechanics of water sharing identified in this study, specifically the Tektek and Masa Gilir position, make the Subak one of the most sophisticated examples of community-based resource management in human history. When interpreted through Elinor Ostrom's Common-Pool Resource (CPR) theory, the Subak fulfills all eight design principles for long-term institutional sustainability [17] . Recent scholarship has extended Ostrom's framework to examine how traditional institutions, such as Subak, respond to 21st-century pressures, including climate variability and digital transformation [20]. These contemporary applications confirm that the CPR model remains analytically robust when applied to living heritage landscapes, provided that it accounts for the spiritual and cosmological dimensions that formal institutional theory tends to overlook. The *Awig-awig* (customary law) serves as a robust institutional framework for managing the "subtractability" of water, ensuring that upstream users do not deplete the resource at the expense of downstream farmers. This creates a "polycentric governance" model that is often more efficient and resilient than the top-down, technocratic irrigation schemes favored by state governments. Central to this governance is the role of the water temple network, which Lansing [21] famously described as a decentralized "biological computer." Our observations confirm that the ritual cycles at the *Pura Ulun Danu* and village-level shrines are not mere superstitions; they are functional ecological triggers that synchronize the irrigation schedule across hundreds of hectares. This synchronization is crucial for pest management and hydrological efficiency. By coordinating the flooding and fallowing of fields through religious calendars, the Subak achieves a level of "automated regulation" that modern bureaucratic systems, which rely on manual monitoring and individual water meters, cannot replicate.

Moreover, the resilience of the Subak's water governance lies in its "deliberative democracy." The *Sangkap* (Subak meeting) serves as a forum where every member has a voice in determining water allocation during times of scarcity [22]. This democratic deliberation fosters a high degree of mutual trust and social cohesion, which is essential for the collective maintenance of the tunnels (*Awed*) and weirs (*Temuku*). In a world where water conflicts are escalating due to climate change and urbanization, the Subak offers a scalable model of "socially embedded technology." It proves that sustainable resource management is not just a matter of engineering, but of building strong social institutions that can resolve conflicts through consensus and shared identity.

4.3. Vulnerability in the "UNESCO Zone": The Political Economy of Landscape Commodification

The most critical challenge facing the Subak today is what this research identifies as 'Unbalanced Landscape Commodification." This phenomenon occurs when the tourism sector, such as villas, luxury resorts, and high-end restaurants, commodifies the beauty of the Subak landscape without contributing to the maintenance of the underlying infrastructure. Our findings reveal a predatory economic relationship: the more "beautiful" the Subak appears, the more developers are incentivized to convert the surrounding land into commercial properties. This conversion often results in the fragmentation of the ancient *Awed* tunnels, which were designed to serve a contiguous agricultural landscape rather than a patchwork of concrete foundations and septic tanks [23]. The "policy-practice gap" between formal state regulations and the reality on the ground in Gianyar is stark. While the Indonesian government has implemented the Sustainable Food Agriculture Land policy to curb land conversion, the financial incentives offered to farmers are grossly insufficient compared to the speculative prices offered by real estate developers. This research indicates that the state's technocratic approach fails to address the "opportunity cost" borne by the

farmers. As a result, UNESCO buffer zones are becoming hotspots for land speculation, where "cultural heritage" becomes a luxury commodity for tourists while the farmers who create that heritage are pushed to the economic margins.

However, the study also documented a growing sense of "Institutional Agency" among the Subak leaders. In response to the encroachment of tourism, several Subak units have begun imposing "Environmental Levies" on new commercial establishments that use their irrigation channels or landscape views. This represents a nascent Rural Social Contract, where the community reclaims its right to manage its ancestral territory. We argue that for the Subak to survive, this form of "indigenous resistance" must be formalized and supported by legal frameworks. The tourism industry must be held accountable as a 'water consumer' and 'landscape beneficiary,' shifting from an asymmetric dependency to a mutualistic relationship that contributes to the funding and restoration of the ecosystem.

4.4. Decolonizing Rural Science through Traditional Ecological Knowledge (TEK)

Finally, the discussion must address the role of Traditional Ecological Knowledge (TEK) in the "decolonization" of rural development. For decades, the "Green Revolution" paradigm has viewed traditional practices as obstacles to modernization, replacing indigenous seeds and lunar calendars with standardized chemical inputs and mechanical technologies. The Subak system, however, provides a direct challenge to this narrative [24]. By using the Wariga (astronomical calendar), the Subak maintains an agroecological system that is naturally synchronized with the earth's rhythms, achieving a level of sustainability that aligns perfectly with the United Nations (UN) Sustainable Development Goals (SDGs).

The ecological wisdom embedded in the Subak, such as the use of ducks for pest control, flooding fields to suppress weeds, and reliance on local organic matter for soil fertility, represents a "cutting-edge" approach to Climate-Smart Agriculture (CSA). Unlike industrial farming, which leads to soil acidification and water pollution, the Subak's "Ritual Ecology" maintains the health of the Pakerisan watershed. This study argues that the global scientific community must recognize the Subak not as a "primitive" relic, but as a sophisticated socio-technical system that offers viable solutions to the environmental crises of the 21st century.

Furthermore, the survival of the Subak as a multifunctional landscape depends on its ability to evolve into a hybrid system. While the younger generation may be reluctant to engage in back-breaking manual labor, they are increasingly seeing the Subak as a platform for digital-based "Agri-tourism" and ecological education. This "New Countryside" model enables economic diversification without compromising the ecological integrity of the land. By protecting the Subak, we are protecting a living archive of human resilience. The goal of future rural policy should not be to "modernize" the Subak by replacing its core values, but to "empower" it by providing the legal and financial tools necessary to defend its indigenous science against the pressures of global capitalism.

4.5. Subak versus Modern Irrigation Systems: A Comparative Institutional Analysis

The contrast between the Subak system and contemporary state-engineered irrigation schemes reveals a fundamental divergence in the philosophy of water governance. Modern irrigation infrastructure, typically designed by centralized government agencies, prioritizes hydrological efficiency through concrete canals, automated sluice gates, and standardized water allocation formulas. While such systems demonstrate measurable gains in short-term water delivery speed, they systematically strip away the social and ecological intelligence embedded within traditional arrangements [5]. The Subak, by contrast, treats water not as a commodity to be distributed but as a sacred communal resource to be collectively negotiated, making its governance architecture fundamentally more adaptive to local ecological variability.

From an institutional design perspective, the critical weakness of modern irrigation systems lies in their dependence on external bureaucratic oversight. State-managed schemes require permanent government personnel to monitor water flow, adjudicate disputes, and maintain physical infrastructure, creating a costly dependency that becomes unsustainable when budgets shrink or political priorities shift [11]. The Subak, in contrast, is entirely self-financing and self-governing through its Awig-awig (customary law)

and the social pressure of community membership. This internal accountability mechanism means that maintenance of the Temuku (water dividers) and Awed (underground tunnels) is carried out voluntarily by farmers who directly depend on the system's integrity, a level of institutional commitment that no bureaucratic monitoring system can replicate.

Furthermore, the ecological outcomes of both systems diverge significantly over time. Longitudinal studies of green revolution-era irrigation schemes across Southeast Asia have documented progressive soil degradation, declining water quality, and increasing pest resistance resulting from the chemical-intensive monoculture farming enabled by modern irrigation [4]. The Subak's synchronized flooding and fallowing cycles, guided by the Wariga astronomical calendar, actively prevent such degradation by maintaining soil microbiome diversity and naturally suppressing pest populations without chemical intervention. This comparison underscores a critical insight: technical efficiency in water delivery does not equate to ecological sustainability in agricultural outcomes.

However, this study does not argue for a wholesale rejection of modern hydraulic engineering. Rather, the findings suggest that the most resilient irrigation governance model is a hybrid one where the precision of modern hydrological measurement is placed in the service of traditional communal decision-making rather than replacing it. Several Subak units in Tabanan and Gianyar have already begun integrating Geographic Information System (GIS) technology to map water flow and detect encroachment points in real time, while retaining the Sangkap (communal meeting) as the ultimate authority over water allocation decisions [25]. This hybrid model demonstrates that indigenous governance systems are not static relics incompatible with modernity, but dynamic institutions capable of selectively absorbing technological tools without surrendering their core social values. The global policy implication is clear: sustainable rural water management in the 21st century requires the decolonization of irrigation science, moving away from the assumption that modern engineering is inherently superior, toward a pluralistic framework that recognizes indigenous hydraulic knowledge as a legitimate and empirically validated foundation for environmental governance [26].

4.6. Limitations and Future Research Directions

This study acknowledges several limitations that should be considered when interpreting its findings. First, the purposive sample of five informants, while sufficient for achieving thematic saturation within a qualitative framework, limits the generalizability of the findings to other Subak units across Bali or other indigenous irrigation systems globally. Second, the 40% reduction in pesticide use reported by farmers represents a perceived trend based on self-reported accounts rather than objectively measured agricultural data; longitudinal soil testing and crop monitoring would be required to validate this figure empirically. Third, the study was conducted within a specific geographic and cultural context, the Pakerisan watershed in Gianyar Regency, and caution should be exercised before transferring its policy recommendations to other regional contexts without further adaptation. Future research should expand the participant base to include Subak units from other regencies, incorporate quantitative hydrological and ecological measurements, and explore the long-term effects of digital agri-tourism on the structural integrity of the irrigation system."

5. Conclusions

This research concludes that the Subak system of Bali, as a UNESCO-recognized Cultural Landscape, is a premier global model for environmentally sustainable rural development. By integrating the Tri Hita Karana philosophy, the Subak has successfully balanced the spiritual, social, and ecological dimensions of land management for over a millennium. The sophisticated institutional mechanisms of *Tektek* and the ecological synchronization of the *Wariga* calendar prove that indigenous governance is the most stable and resilient foundation for managing common-pool resources in the face of modern environmental stress. However, the 'Outstanding Universal Value' of the Subak is currently threatened by the unbalanced commodification of its landscape for tourism and the fragmentation of its ancient hydrological infrastructure." This study highlights a critical need for a "New Rural Social Contract," in which the tourism industry must be legally and financially obligated to support farmers' ecological labor. We argue

that the future of the "New Countryside" in Indonesia depends on the formal legal recognition of Subak customary laws (*Awig-awig*), allowing these traditional institutions to operate as modern environmental authorities. Ultimately, the Subak is more than just a site of agricultural production; it is a vital ecological buffer and a living manifestation of a harmonious human-nature relationship. Protecting the Subak is not an act of cultural nostalgia, but a strategic imperative for global environmental sustainability. By empowering the Subak as the primary guardian of the watershed, we can ensure that Bali's rural landscapes remain resilient, productive, and meaningful for generations to come.

Author Contributions

Conceptualization, A.A. and M.N.H.; methodology, A.A.; software, M.N.H.; validation, A.A. and M.N.H.; formal analysis, A.A. and M.N.H.; investigation, A.A. and M.N.H.; resources, A.A.; data curation, M.N.H.; writing—original draft preparation, A.A.; writing—review and editing, M.N.H.; visualization, M.N.H.; supervision, A.A.; project administration, A.A. Both authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Ethical review and approval were waived for this study because it primarily involved non-invasive interviews with key informants in their professional capacities. The study did not involve sensitive personal data, medical procedures, or vulnerable groups, and ensured participants' full anonymity in accordance with standard qualitative research ethics.

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study. All participants were informed about the purpose of the research and voluntarily agreed to participate, with the understanding that their identities would be protected using initials.

Data Availability Statement

The data presented in this study are available on request from the corresponding author. The raw data are not publicly available due to the privacy of the informants and the protection of local customary information.

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Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

The authors confirm that they used artificial intelligence (AI)-assisted tools, including large language models, during the preparation of this manuscript. AI tools were utilized to assist with language editing, grammatical refinement, and structural clarity of the written text. All scientific content, data collection, field observations, interview analysis, theoretical interpretation, and conclusions presented in this manuscript are entirely the original work of the authors. The authors take full responsibility for the integrity and accuracy of all content published herein, and all AI-assisted outputs were critically reviewed and validated by the authors prior to submission.

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