Potential Sustainability of Integrated Household Constructed Wetlands (IHCWS) implementation in small island as an effort to mitigate marine pollution due to greywater domestic wastewater (A case study in Bungin Island, Indonesia)

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Abstract. The potential for surface marine water pollution from domestic greywater wastewater poses a threat to small, densely populated islands. This condition will affect the sustainability of the ecosystem in the surrounding environment. This research was conducted on Bungin Island, located in Sumbawa Regency, Indonesia. The island is one of the most densely populated islands with an area of only 8.5 ha and a population of 3,400 people. This research aims to map the potential sustainability of the application of Integrated Household Constructed Wetlands (IHCWS) on Bungin Island, Indonesia as an alternative to managing greywater from household activities. There are six dimensions and thirty sustainability attributes studied including ecology, socio-culture, economy, technology, policy, and public health. The data obtained were analyzed using the RAPFISH MDS method. The results showed that the potential application of IHCWS on Bungin Island in each aspect, ecology (88.68%), socio-culture (79.13%), economy (99.66%), technology (99.71%), policy (99.71%), and public health (88.68%). In conclusion, the IHCWS is classified as sustainable. The application of technology that requires maintenance is not by the conditions of small island communities. This is one of the sustainable solutions to mitigate environmental pollution, especially marine in small islands that have a high population density.

1 Introduction

A multitude of anthropogenic and environmental factors, such as increasing urbanization and climate change, are placing an unparalleled burden on the water supply chain [1]. Inadequate management of the growing volume of household wastewater that directly flows into water bodies leads to pollution issues affecting the carrying capacity and surface water quality. In

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addition, domestic wastewater can disrupt aquatic habitats, therefore compromising the biodiversity of both ecosystems and aquatic landscapes [2]. Lack of treatment of household wastewater poses a threat to aquatic and marine organisms and is responsible for several airborne and wastewater-associated illnesses [3].

Domestic wastewater consisting of black water and greywater (from shower drains and washing facilities) represents the largest portion of the overall wastewater stream. More than 90% of domestic wastewater in developing countries is stored or discharged without any treatment into surrounding rivers, lakes and marine areas causing serious ecological problems such as water quality degradation and impacted biodiversity loss [4]. Greywater is composed of several contaminants, including both organic and inorganic compounds. Kitchen-sourced domestic wastewater is characterized by a higher concentration of carbon and a relatively high presence of coliform organic pollutants. In contrast, sewerage generated from residential bathrooms primarily consists of suspended sediments, mineral salts, nutrients, organic compounds, and pathogens [5]

Bungin Island is one of the small islands in Sumbawa Regency with a very high population density. Bungin Island is predominantly inhabited by the Bajo tribe. Bajo people are known as people who live in the sea and coastal areas. Initially this area was only 2 ha, but it was expanded with a reclamation system to 8.5 ha. Bungin Island consists of dead coral piles and soil. The characteristics of the land constituents on Bungin Island mean that the filtration process of domestic wastewater that is simply discharged does not work properly. So this can have an impact on environmental pollution around Bungin Island. Basic sanitation conditions are still not well implemented on Bungin Island. Clean water problems, sanitation problems and domestic wastewater management are still the main problems on Bungin Island [6].

The management of greywater domestic wastewater is not a new issue, but the sustainability of the system is still a problem. Household wastewater treatment based on conventional sanitation concepts is the most common approach, which is neither environmentally nor economically friendly. In order to realize sustainable sanitation solutions, there is a need to develop alternative sustainable sanitation systems [4].

Currently, many domestic wastewater management technologies are developing either physically, chemically, biologically or even a combination of the three. However, for developing countries, especially coastal areas, the utilization of technology cannot be done simply by using technology without thinking about the basic conditions of the region. Domestic wastewater management conditions will produce a satisfactory and sustainable system if supported by community behaviour and government policies [7].

This study proposes the usage of Integrated Household Constructed Wetlands (IHCWS) as a strategy. Many factors were taken into account when choosing the technology for this sustainable home wastewater treatment model scenario. The community's low level of knowledge, middle-class to lower-class economic status, and citations to local sanitation systems and technological alternatives are taken into account. The adoption of local sanitation systems is described as involving social transformation in addition to the basic application of technology in the reference to particular regional sanitation systems and technology possibilities [8]. If the public is to accept better sanitation conditions in both urban and rural areas, then related social and cultural factors need to be considered during the planning and implementation process [9].

The system is made up of a two-stage sedimentation tank and a vertical-flow built wetland bed. The precast structure is durable and weatherproof. Modular structure enables for installation by untrained workers. The technique is expected to overcome local restrictions, such as soil conditions and unskilled building [10]. This research describes an innovative on-site wastewater treatment system (Integrated Household Constructed Wetlands, IHCWS) for treating domestic wastewater on small islands. This method appears to have advantages for

home wastewater treatment on small islands, where low cost, convenient installation, and operating simplicity are critical. Furthermore, the literature study demonstrates that IHCWS technology provides management benefits that can be applied in land-constrained situations like Bungin Island.

The aim of this study was to mapping the potential for sustainability in the use of IHCWS as a domestic greywater wastewater management system on Bungin Island.

2 Materials and Methods

The trial was conducted in the front yard of a family home located on Bungin Island, Sumbawa Regency, Indonesia. The system comprised a two-stage sedimentation tank and a vertically fabricated wetland bed segment. The frame construction was composed of highly durable and waterproof fiber glass cloth and acrylic. In the plan view, the structure is circular, with a lower bottom than a higher top, in order to simplify transportation. Installation can be carried out immediately following excavation. The two-stage sedimentation tank is divided into two segments, each allocated an empty-bed volume of 0.5 m^3. The overall volume capacity of the marsh bed section is 1 cubic meter, divided into an area of 1 square meter and a depth of 1.0 meter. The engineered wetlands system comprises an initial section completely filled with soil, succeeded by a second layer entirely filled with husk charcoal, and ultimately a third section entirely filled with gravel. Eventually brimming with sand sourced from the ocean. Every hierarchical level of the system integrates organic filters derived from easily accessible resources found on Bungin Island. A 10 cm layer of washed gravel with a particle size of 10–30 mm, a 15 cm layer of washed husk charcoal with a particle size of 5–12 mm, and a 30 cm layer of washed sand were modified according to the standard design criteria [10]. To allow intermittent system husk charcoal, gravel, and sand to flow into the first segment from the inlet basin and then into the second segment via a floating valve deployed in the first segment.

The plant utilized in this investigation was *Typha angustifolia*, which was sown in the vertical flow wetland bed segment. Several factors led to the selection of *Typha angustifolia* as the wetland plant. Notable features include weather resistance and visual appeal. In April 2024, the plants were transplanted into a distinct planting system and thereafter subjected to uninterrupted irrigation with residential graywater for a duration of one month. Once it was determined that the development of the plants did not result in any adverse consequences, they were transferred to the IHCWS system. Research and observation activities took place between May 2024 and August 2024. Throughout the experimental operation, the influent of domestic wastewater consisted of effluents from kitchen and washing machines. The daily provision of wastewater capacity amounted to 100 liters. Samples of domestic graywater effluent were collected for laboratory analysis prior to treatment. The laboratory testing is conducted by the State Environmental Laboratory of West Nusa Tenggara, Indonesia, which holds national accreditation. Domestic graywater wastewater criteria are defined in Ministerial Regulation 68/2016 of the Ministry of Environment and Forestry, which sets national standards for the quality of domestic wastewater. The parameters investigated comprise BOD, COD, TSS, pH, oil and grease content, and Total Coliform.

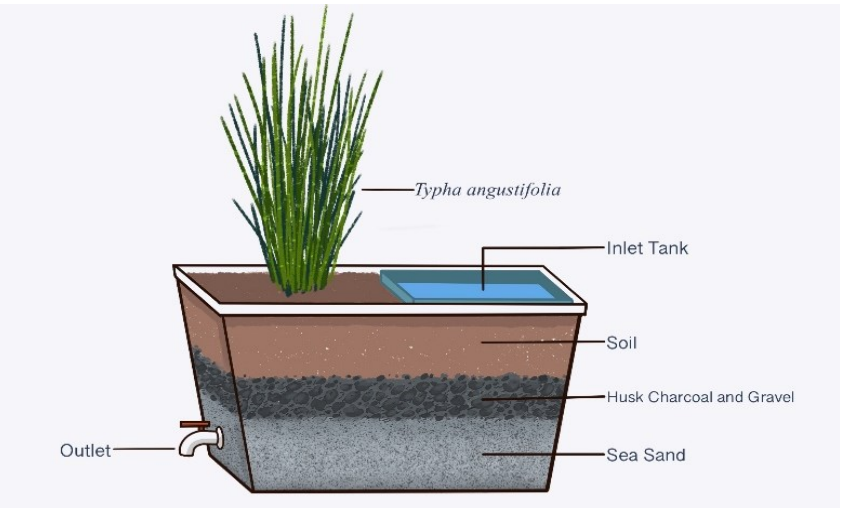


Figure 1. Prototype of Developed IHCWS

This study investigates the ecological, socio-cultural, economic, policy, public health, and technical dimensions of sustainability. The categorization of dimensions and attributes is presented in Table 1.

Table 1. The Classification of Dimensions and Attributes of Sustainability

Dimension	Attributes
Ecology	Nutrient Removal
	Reuse Potential
	Sludge Quantity
	Land area required
	Odor/Sound/Insects
Economic	Operational Costs
	Maintenance Costs
	Initial investment cost
	Costs from the community
Socio-cultural	Public Acceptability
	Aesthetic Value
	Community Participation
	Technical Labour Requirements
	Awareness
	Cultural Support
Technology	Installation Durability
	Installation Safety
	Scale (Small/Onsite/local)

	Practical in Implementation
	Installation Raw Material Availability
Public Health	Public Health Impact
	Environmental Health Issues
	Wastewater system safety
	Disease Vectors
	Environmental Toxicity
Policy and Institutionalization	Availability of Rules
	Coordination of government elements
	Rule Implementation
	Increased Public Education and Awareness
	Effectiveness Participation of all elements/stakeholders

(Source : [11], [12], [13], [14], [15], [16])

To gather quantitative data on sustainability, in addition to obtaining data from laboratories and 274 community members on Bungin Island, qualitative data was also obtained through in-depth interviews with 6 experts from multi-stake holders. The collected data was then analyzed using RAPFISH Multi-Dimensional Scaling. Thus, the sustainability value of each indication is acquired.

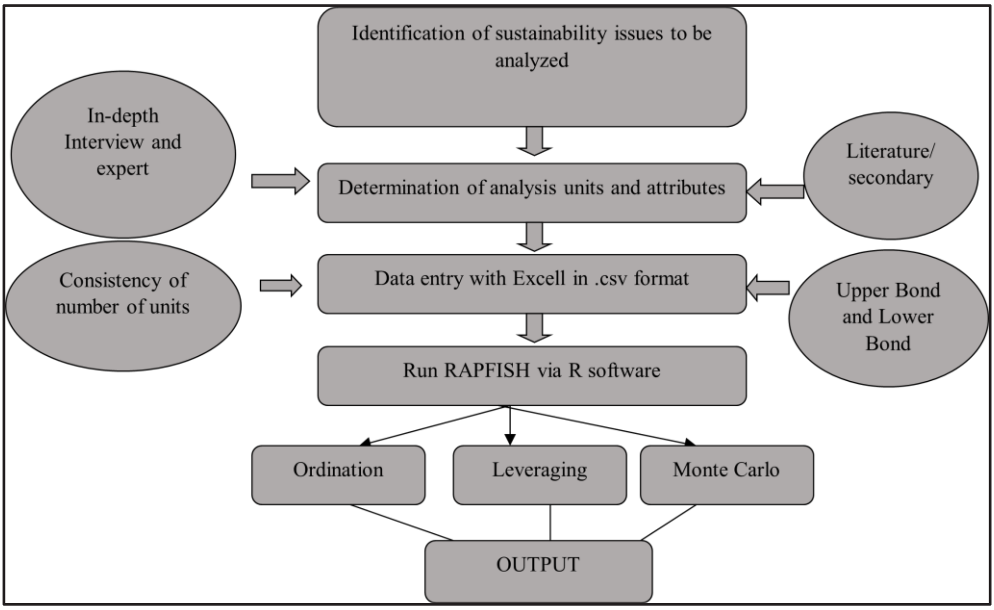


Figure 2. RAPFISH Software Architecture

After the assessment process using RAPFISH Software, it is continued with the interpretation of the sustainability category with Table 2.

Table 2. Sustainability Indicator Rating Categories

Index Value	Category
0 – 25	Not Sustainable
>25 – 50	Less Sustainable

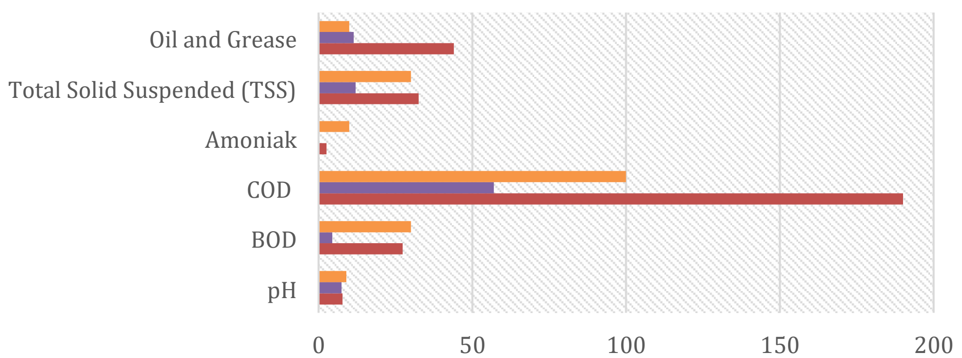
>50 – 75	Moderately Sustainable
>75 – 100	Sustainable

3 Result and Discussion

3.1 Laboratory analysis results

The residential wastewater from the public toilets was collected as raw wastewater and subsequently treated. This treated wastewater was then used as an input for the Integrated High-Capacity Wastewater System (IHCWS). Ministerial Regulation 68/2016 of the Ministry of Environment and Forestry establishes national criteria for the quality of household wastewater, according to which domestic wastewater parameters are defined. Analysed parameters include BOD, COD, TSS, pH, oil and grease concentration, and total coliform.

The analysis revealed that several indices, including COD, Total Suspended Solid (TSS), Oil and Grease, and Total Coliform, surpassed the established quality criteria. Next, the residential greywater effluent underwent testing using IHCWS. The test findings indicate that the COD and TSS values satisfy the approved quality criteria. Hence, the components that yet fail to satisfy the quality criteria are the presence of oil and grease, as well as Total Coliform.



	pH	BOD	COD	Amoniak	Total Solid Suspended (TSS)	Oil and Grease
Quality Standart	9	30	100	10	30	10
IHCWS	7,5	4,42	57	0,15	12	11,4
Pra Treatment	7,78	27,31	190	2,63	32,5	44

Figure 3. Laboratory Analysis Results

The graph highlights the effectiveness of IHCWS in treating most parameters within acceptable Quality Standards, except for a minor exceedance in oil and grease. Pre-treatment values show that without treatment, the wastewater contains high levels of COD, TSS, and oil and grease, requiring significant intervention.

3.2 Sustainability Analysis

3.2.1 Ecological Dimension Sustainability

The attributes estimated to be indicators of sustainability in the ecological dimension are (1) Nutrient removal, (2) Wastewater reuse potential, (3) Sludge quantity, (4) Land area required, (5) Odor, Sound and Insects.

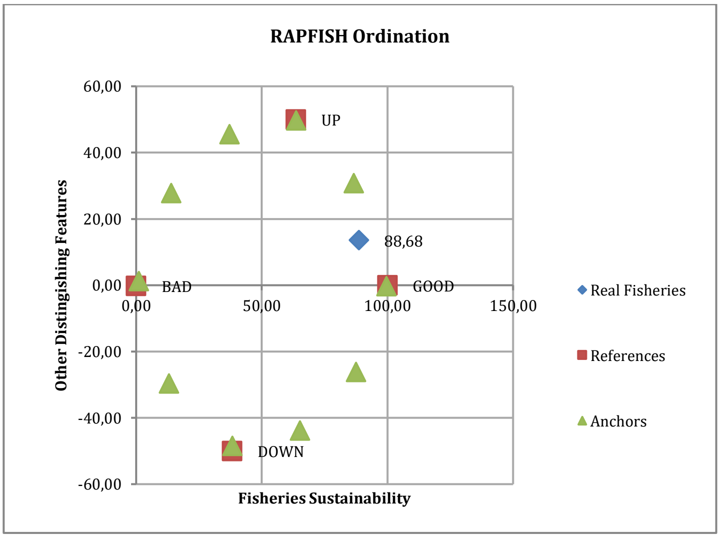


Figure 4. IHCWS sustainability status index Ecological Dimension

Figure 4 displays the results of the MDS analysis performed using RAPFISH. The analysis reveals that the ecological state of the IHCWS model created on Bungin Island has an ecological dimension sustainability index value of 88.68%. According to the sustainability status classification, this number is indicative of the ecological dimension of the IHCWS being classified as sustainable.

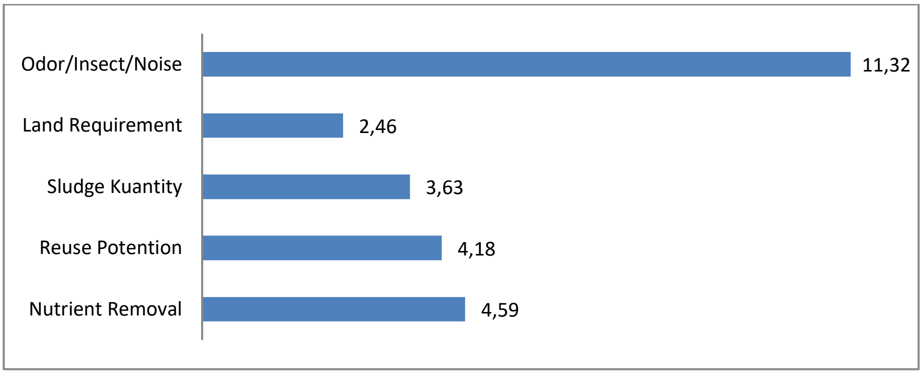


Figure 5. IHCWS Leverages Value Ecology Dimension

After conducting a leverage analysis of the characteristics in the ecological dimension shown in Figure 5. Three attributes were identified as sensitive to the sustainability index of the ecological dimension of the IHCWS. These attributes are: odor/sound and insects (11.32%), nutrient removal (4.59%), and potential reuse of wastewater (4.18%).

Constructed wetlands (CWs) are ecological effective and sustainable engineered systems for domestic and/or municipal wastewater treatments. In the last half-century, CWs have become common solutions for small communities in remote mountainous areas. However, cold climate in mountain environment often causes a significant reduction of the pollutant removal performance compared to warmer environments [17].

3.2.2 Economic Dimension Sustainability

Attributes that are estimated to be indicators of sustainability in the economic dimension are (1) Operational Costs, (2) Maintenance Costs, (3) Initial investment costs, (4) Costs from the community.

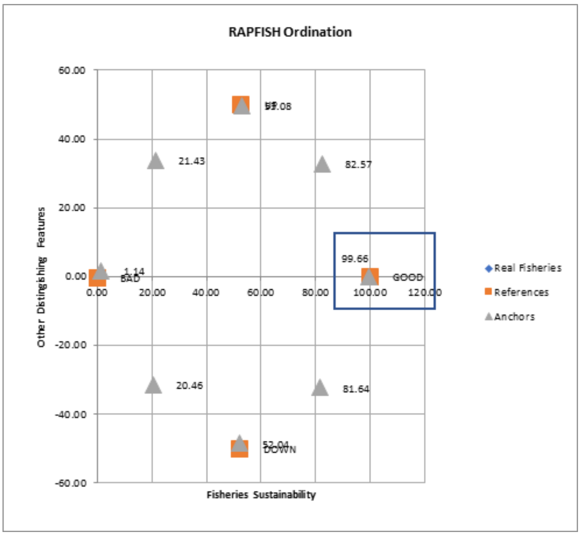


Figure 6. IHCWS sustainability status index Economic Dimension

Figure 6 displays the results of the MDS analysis performed using RAPFISH. The assessment reveals that the economic condition of the IHCWS model created on Bungin Island has an ecological dimension sustainability index value of 99.66%. According to the sustainability status classification, this score is indicative of the economic dimension of the IHCWS being classified as sustainable.

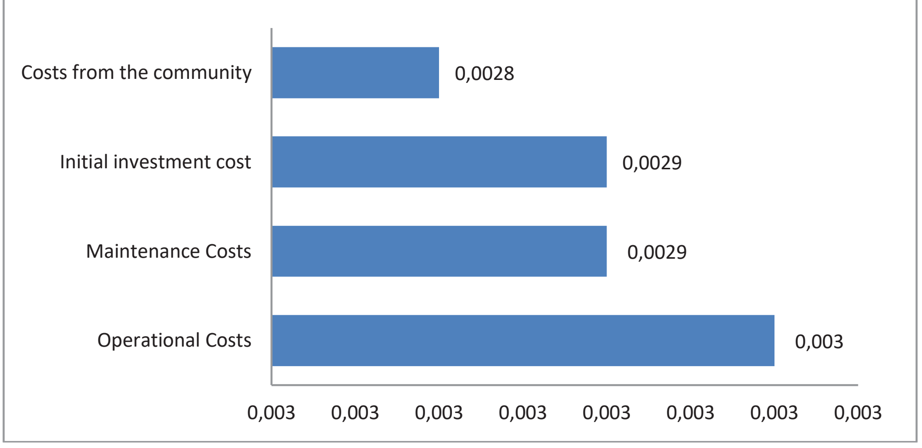


Figure 7. IHCWS Leverages Value Economic Dimension

Based on the findings of the leverage analysis of the characteristics in the economic dimension shown in Figure 7. Three attributes were identified as sensitive to the sustainability index of the economic dimension of the IHCWS. These attributes are operational costs, maintenance costs, and initial investment costs.

The economic aspect is also a challenge in domestic wastewater management as the low willingness to pay of the community is a major factor. Thus, the use of IHCWS is economically supportive as it does not require large initial investment and operational costs. The ideal configuration of wastewater treatment system (WTS) for attending cities specificities has become a complex decision, due to the fact that there are several available technologies, and a diversity of characteristics presented in the scenario of each city. Considering the importance of

economic analysis, especially in developing countries, this work aims to demonstrate the economic feasibility considering cost-related indicators for the ideal WTS selection for specific features [18].

3.2.3 The sustainability of the socio-cultural dimension

Public acceptability, Aesthetic Value, Community Participation, Technical Worker Needs, Awareness, and Cultural Support are the assessed traits that serve as markers of sustainability in the social dimension.

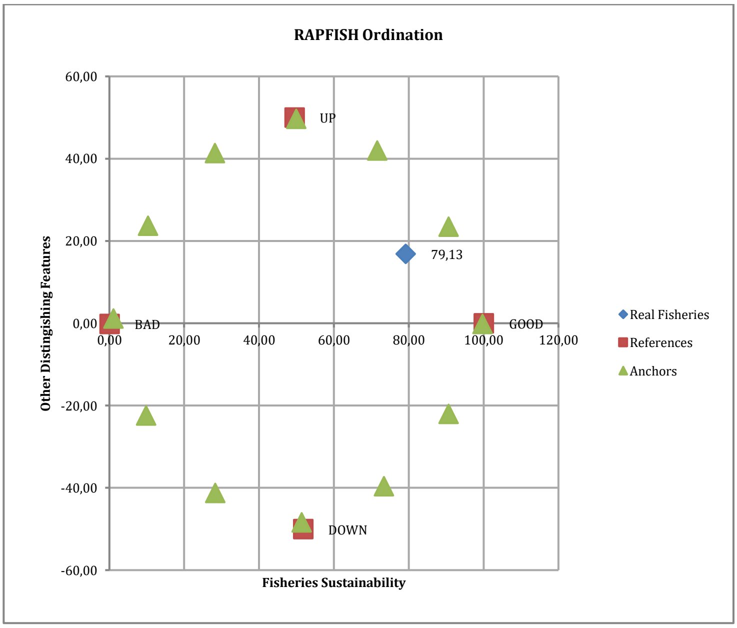


Figure 8. IHCWS sustainability status of socio-cultural dimension

Based on the MDS analysis performed using RAPFISH, the findings presented in Figure 8 reveal that the socio-cultural circumstances of the IHCWS model created on Bungin Island have a sustainability index value of 79.13% for the socio-cultural dimension. According to the sustainability status classification, this value signifies that the socio-cultural layer of the IHCWS falls inside the sustainable category.

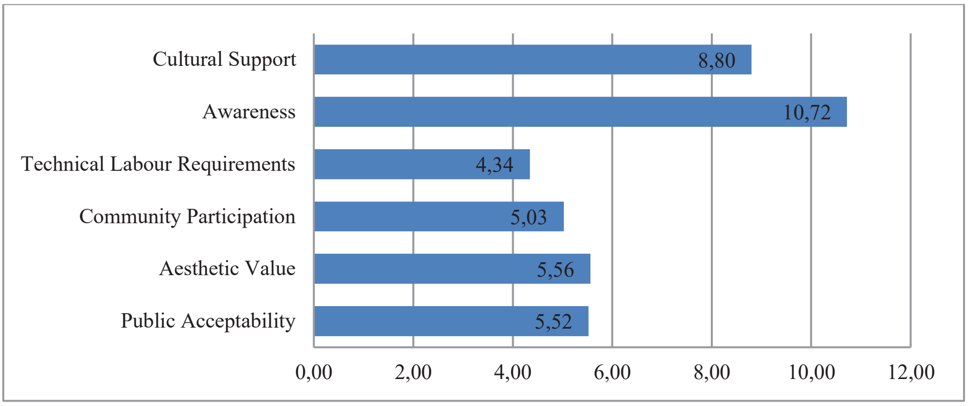


Figure 9. IHCWS Leverages Value Socio-Cultural Dimension

Utilizing the leverage analysis of the attributes in the socio-cultural dimension shown in Figure 9, three attributes were identified as sensitive to the sustainability index of the socio-cultural dimension of the IHCWS. These attributes are Awareness (10.72%), Cultural Support (8.8%), and Aesthetic Value (5.56%).

The social aspect is key because the community is one of the main actors in supporting the sustainability of the system [19]. Then, the thing that needs to be considered is the factor of community habits that have emerged over the years. A culture-based approach can also be a solution. This can also be applied on Bungin Island because the region is still close to its traditional values.

3.2.4 The Sustainable Public Health Dimension

The features identified as indicators of sustainability in the Public Health dimension include: (1) Impacts on Public Health, (2) Issues related to Environmental Health, (3) Safety of Wastewater Systems, (4) Vehicles for Disease Transmission, and (5) Toxicity of the Environment.

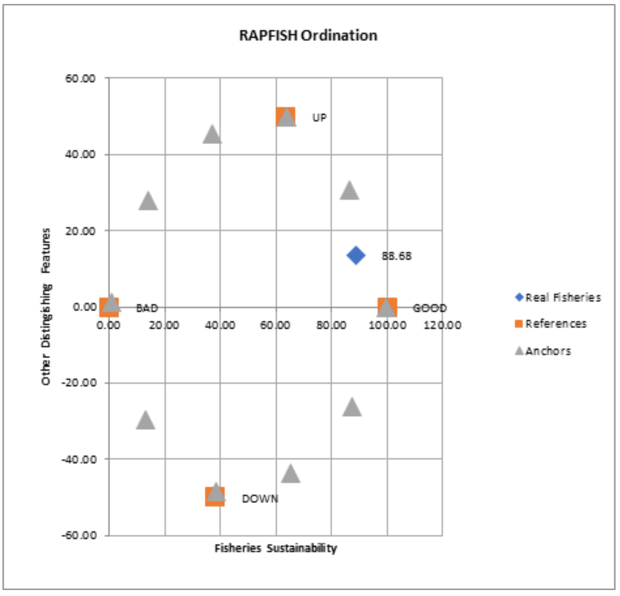


Figure 10. IHCWS sustainability status of Public Health Dimension

The findings from the MDS analysis performed using RAPFISH, as shown in Figure 10, reveal that the public health condition of the IHCWS model created on Bungin Island has a sustainability index value of 88.68% for the public health dimension. According to the sustainability status classification, this number signifies that the public health sector of the IHCWS falls inside the sustainable category.

After conducting a leverage analysis of the attributes in the Public Health dimension as shown in Figure 11, three attributes were identified as sensitive to the sustainability index of the Public Health dimension of the IHCWS. These attributes are Environmental Toxicity (11.32%), Public Health Impacts (4.59%), and Environmental Health Issues (4.18%).

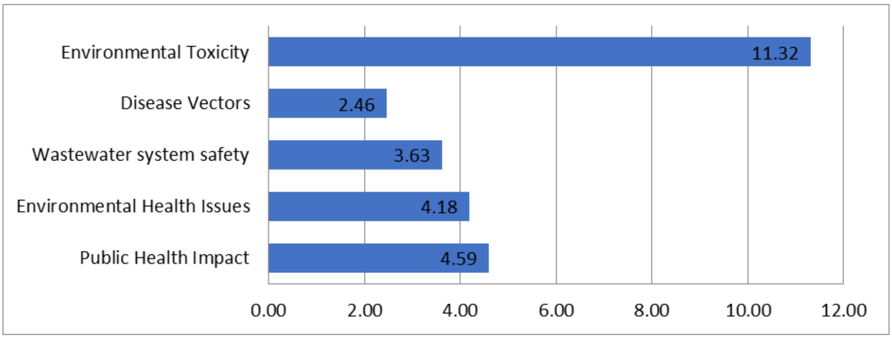


Figure 11. IHCWS Leverages Value Public Health Dimension

The public health aspect of domestic wastewater treatment systems is crucial in preventing disease and protecting communities from potential health hazards. Untreated wastewater contains harmful pathogens, chemicals, and contaminants that can lead to waterborne diseases such as cholera, dysentery, and typhoid, as well as chronic health problems due to exposure to toxic substances. Effective treatment systems play a key role in reducing or eliminating these risks by removing pathogens and neutralizing harmful chemicals, thus safeguarding water sources and ensuring they are safe for drinking and other uses [20], [21].

3.2.5 Dimension of Technological Sustainability

The Technology dimension is considered to comprise five properties that serve as indicators of sustainability: Installation Durability, Installation Safety, Installation Scale, Practicality in implementation, and Availability of Installation Raw Materials.

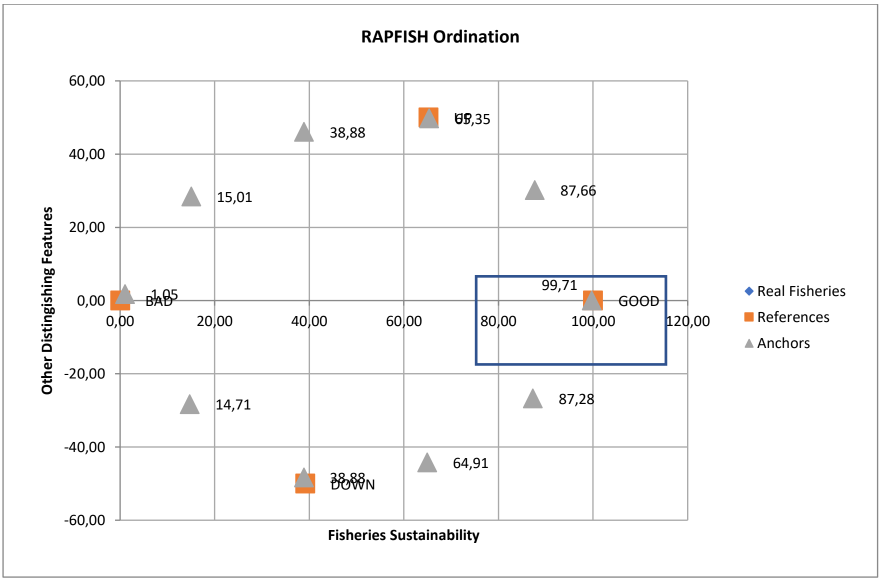


Figure 12. IHCWS sustainability status of Technological Dimension

The MDS analysis performed using RAPFISH, as shown in Figure 12, indicates that the operational state of the IHCWS model created on Bungin Island has a sustainability index value of 99.71% for its technical component. According to the sustainability status classification, this score is indicative that the technical aspect of the IHCWS falls inside the sustainable category.

According to the findings of the leverage analysis of the criteria in the technology dimension shown in Figure 13 the installation scale attribute (0.9%) is identified as the most sensitive to the sustainability index of the technology dimension of the IHCWS.

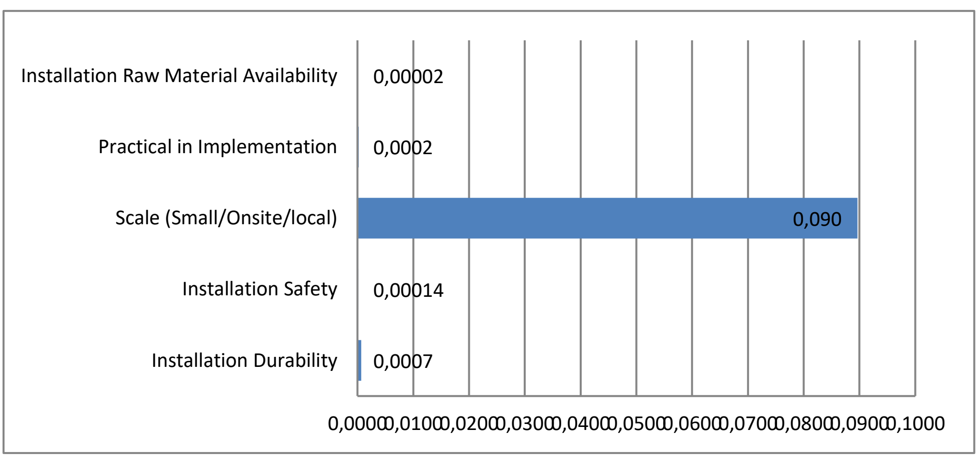


Figure 13. IHCWS Leverages Value of Technology Dimension

Currently, much of the wastewater is released into the environment near its generation point without proper treatment. To enhance sanitation and environmental conditions, it is crucial for environmental scientists and engineers to devise sustainable methods for treating and safely discharging domestic wastewater close to its source. Developing ecologically

friendly and economically feasible on-site wastewater treatment technologies is a promising solution for significantly reducing water pollution. Moreover, these systems should be straightforward and cost-effective in terms of construction, management, and maintenance to ensure they are practical for stakeholders [22].

3.2.6 Policy and Institutional Dimension Sustainability

The attributes estimated to be indicators of sustainability in the policy and institutional dimensions are (1) Availability of Rules, (2) Coordination of Government Elements, (3) Implementation of Rules, (4) Increased Public Education and Awareness, and (5) Effectiveness of Participation of All Elements/Stakeholders.

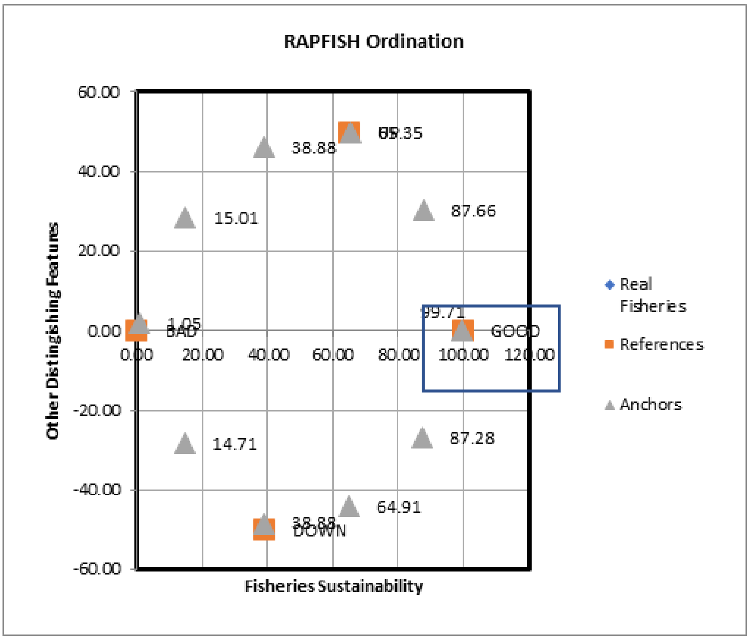


Figure 14. IHCWS sustainability status of Policy and Institutional Dimension

The MDS analysis performed using RAPFISH, as shown in Figure 14, reveals that the Policy and Institutional conditions of the IHCWS model created on Bungin Island provide a sustainability index value of 99.71% for the Policy and Institutional dimension. According to the sustainability status classification, this value is indicative that the Policy and Institutional dimension of the IHCWS falls inside the sustainable category.

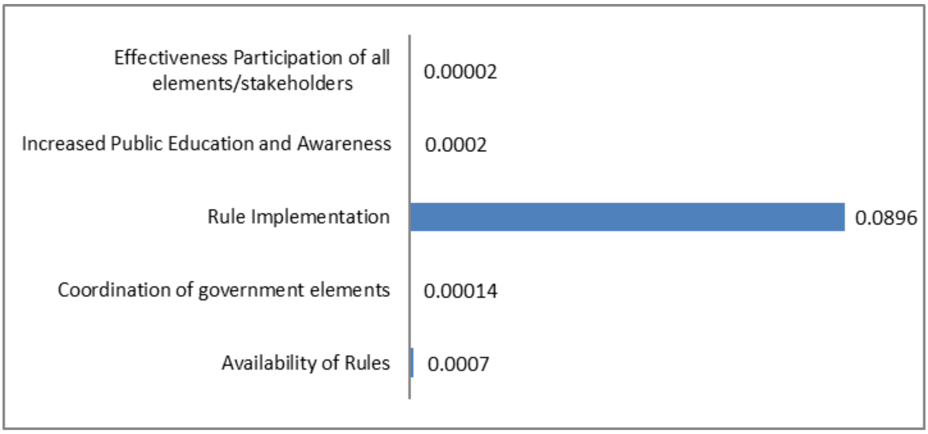


Figure 15. IHCWS Leverages Value of Policy and Institutional Dimension

Through the leverage analysis of the attributes in the Policy and Institutional dimension shown in Figure 15, we have identified the attributes that are deemed sensitive to the sustainability index of the IHCWS. Specifically, the attribute of Implementation of Rules has a sensitivity of 0.9%. Overall, the sustainability scores for each dimension show the scores overlaid on the kite diagram.

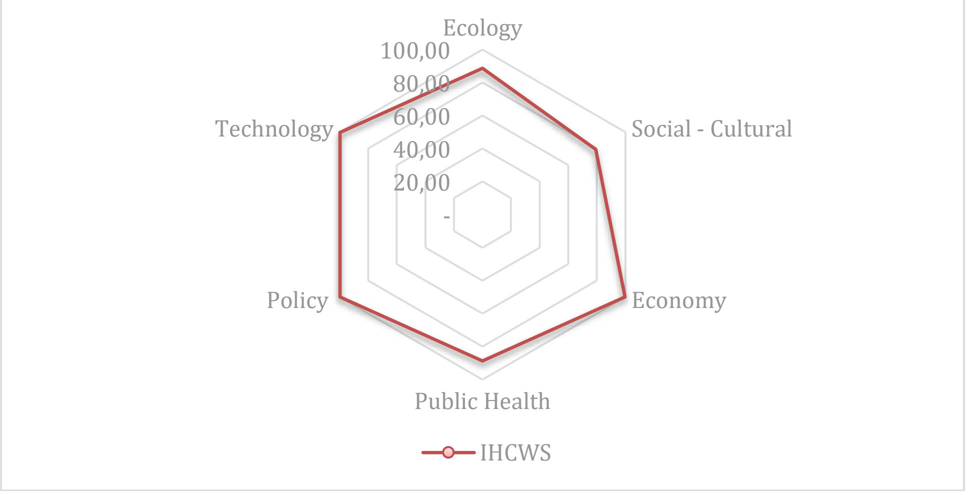


Figure 16. IHCWS sustainability index

The IHCWS demonstrates sustainability in ecology, technology, and socio-cultural aspects but faces critical issues in public health and economic feasibility, with moderate performance in policy. These findings indicate a need for improvements in cost-effectiveness and health impacts to complement its strengths [23].

This research emphasizes on technical aspects, further related research conducted focuses on the use of plants as a phytoremediation system in reducing pollutant levels in domestic wastewater [24]. The results of this study showed that the use of *Typha angustifolia* plants significantly increased nitrogen reduction efficiently and further reduced ecological risks in domestic wastewater [25].

For small islands like Bungin, wastewater management technologies must be simple, effective, and community-adaptable. Current systems often fail due to inadequate technical expertise, institutional capacity, and financial resources in low-income areas. Tailoring

sustainability indicators for these contexts is essential to improve planning and operation [26], [27]. Various studies have proposed sustainability indicators to evaluate the planning or operation of wastewater treatment plants (WWTPs). However, these standard indicators are generally tailored to high and upper-middle income countries, while low and lower-middle income countries face unique challenges. Therefore, developing a set of relevant and effective sustainability indicators specific to the context of these countries is essential to support the planning and operation of small-scale wastewater treatment systems [28], [29].

Research findings show that the lack of education and awareness is also a problem in the implementation of domestic wastewater management. Then, in this case, the community needs to be invited to learn more about the potential risks of domestic wastewater for the environment. The process of educating citizens must start with the simple things first. Thus, the implementation of IHCWS will give better results. This is closely related to the sustainability of environmental management and community understanding [30].

Although, the development of the IHCWS model as an alternative wastewater management on small densely populated islands still has shortcomings, especially in the aspect of E. Coli bacteria, it is still possible to be developed as an environmentally friendly and sustainable solution in domestic wastewater management.

4 Conclusion

The IHCWS is classified as sustainable. The application of technology that requires maintenance is not by the conditions of small island communities. This is one of the sustainable solutions to mitigate environmental pollution, especially marine in small islands that have a high population density.

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