An Assessment of Solar Water Pump System Sustainability in Indonesia: A Multidimensional Scaling Approach

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Abstract: The implementation of solar water pump systems (SWPS) has been increasingly developed, especially in remote areas facing challenges with access to electricity and clean water. However, this technology also has several limitations and challenges that need to be addressed, such as high initial costs, technological and infrastructure limitations, and the need for extensive land areas. This study aims to evaluate the benefits of sustainable solar water pump (SWP) installations in Indonesia, focusing on three main aspects: economic, social, and environmental. Primary data collection was conducted at 35 SWPS installation sites across Indonesia, with 98 responden including installer and applicators (community for drinking water and farmers for irrigation). Primary data analysis was conducted using Multidimensional Scaling (MDS) with the R software as the statistical technique used to visualize the level of similarity or dissimilarity of multivariate data in graphical form. The research results indicate that the overall sustainability score is 58.67, which categorizes the application of SWPS in Indonesia as moderately sustainable. The economic dimension has the highest sustainability score of 66.28, followed by environmental with 55.47, and social with 54.27. This analysis is crucial so that the SWP technology can be recognized, understood, and optimally applied in various regions of Indonesia, especially in areas requiring environmentally friendly and energy-efficient clean water solutions. A comprehensive understanding of the economic impact in terms of cost savings, social benefits in improving community quality of life, and environmental impact related to carbon emission reductions will assist in determining whether this technology is feasible for wide adoption or requires alternative approaches.

Keywords: economic dimension; environmental dimension; social dimension; solar water pump systems (SWPS); sustainability

1. Introduction

The increasing global energy demand, the emissions from the use of scarce primary energy sources, and the associated impact on the environment have brought a challenge to our society[1)]. The development of technology related to renewable energy and its utilization has increased significantly[2)]. The utilization of renewable energy (RE) is a priority for various countries and organizations that contribute to decarbonization by reducing electricity usage, which has an impact on reducing emissions into the atmosphere[3,4)]. Efforts are needed to maintain a balance between industrial development[5,6)] and environmental issues to achieve sustainable development[7,8)]. Environmental concerns worldwide (climate change, global warming, etc.) are pushing to reduce the consumption of fossil fuels[9)].

Electricity generation from renewable and other clean sources can significantly reduce direct and indirect emission[10].

Among various renewable energy sources, solar energy is one of the most abundant and widely available, especially in equatorial regions such as Indonesia[11,12]. Utilization of sunlight as an energy source using photovoltaic (PV), which can be installed on various scales, households[13,14], high-rise buildings[9], industry[15], and water pumps[16]. Solar-powered water pumps are known as Solar Water Pumping Systems (SWPS), where this system is handy in areas with limited electricity[17,18], remote areas[19], and access to clean water that is difficult to reach[20]. SWPS is a water pumping system that utilizes solar energy as a power source to operate a water pump. SWPS consists of solar panels (photovoltaic), water pumps, inverters, and various electronic components that control its operation. Solar panels capture energy from sunlight and convert it into electricity, then drive the water pump. This system allows access to water without relying on conventional electricity grids, especially in remote areas[13].

SWPS have been widely installed to meet the clean water needs of communities[21,22]. SWPS is widely used to provide drinking water in rural or remote areas that do not have access to the electricity grid. This system helps meet the basic need for clean water sustainably. SWPS is also used for irrigation, which previously used diesel power[21]. SWPS is widely used in agriculture, especially in areas far from electricity sources. Farmers can pump water from wells or water bodies to irrigate crops efficiently by utilizing solar energy. This is very important in dry season conditions or areas with water shortages. The use of SWPS for the provision of clean water for communities and irrigation is also widely applied in Thailand[20], India[23], and Africa[24,25]. Furthermore, SWPS is used for water management for livestock and wildlife, conservation, and water management for communities, especially in areas with difficulty sustaining clean water[21].

In Indonesia, the application of SWPS has been increasingly developed, especially in remote areas that have challenges in accessing electricity and clean water. As an archipelagic country with a relatively large rural area, Indonesia needs affordable and environmentally friendly water supply solutions. Most of the applications of SWPS in Indonesia are focused on providing drinking water, especially in remote areas not reached by the PLN electricity network. An example of significant application is in East Nusa Tenggara, where many villages have utilized SWPS technology to pump water from deep wells or other water sources for daily needs. SWPS has also begun to be introduced for agricultural irrigation, although still on a smaller scale than in other countries such as India, Thailand, and Africa. In countries such as India and several African countries, SWPS has become the leading solution for agriculture and irrigation[26]. India, for example, has adopted the SWPS system on a large scale as part of a national effort to reduce dependence on fossil fuels and increase food security through sustainable irrigation[27]. The Indian government has provided massive subsidies to support farmers adopting the SWPS system[27]. In African countries such as Kenya and Ethiopia, SWPS are also very important to address the water crisis in semi-arid areas[28]. These systems help farmers and rural communities access water for agriculture, livestock, and household needs[26]. Many African SWPS projects are supported by international organizations and NGOs focusing on sustainable development and water security[25]. Implementing SWPS in accordance with standards provides economic and non-economic benefits[29].

Although SWPS has many significant benefits in providing clean water and increasing water access in remote areas, this technology also has some limitations and challenges that need to be considered such as high initial costs and dependence on sunlight intensity[30]. Further disadvantages are that the application is limited to small and medium Scales and regular maintenance is still needed to maintain optimal performance[28]. In remote areas, the availability of spare parts or technicians who can repair and maintain the system can be a challenge[13,26]. Problems such as inverter failure, dirty solar panels, or worn-out pumps require technical knowledge that is sometimes not possessed by residents[13,26]. Although the main components of SWPS are relatively simple, integrating the entire system often requires more complex technical expertise. In the event of technical problems, repairs may require assistance from specialized technicians who are sometimes unavailable on-site, especially in remote areas far from urban centers. In addition, SWPS installations also use a large amount of land for solar panel installation, low efficiency under specific conditions, and dependence on other infrastructure[13].

During the design and use of SWPS, there were several problems, or they needed to be by IEC 62253-2011 on Photovoltaic Pumping Systems. Several problems with SWPS installations, mainly found in Indonesia, include non-ideal PV construction, such as being shaded, too low, or too wide, making it difficult to access each module or rusty construction maintenance, which can reduce the PV life cycle[27], pumps installed in water with high iron or mud content[31], not equipped with water meters[13], pumps not flowing or submerged in water[32], in irrigation installations, cables were found to be unprotected, making them prone to being dug or damaged[13], in tropical areas with high rainfall but not equipped with lightning rods[32]. Based on the conditions above, a research gap was obtained, and although SWPS installations provide benefits, obstacles, and deficiencies in this system are still found. So, the research question arises as to whether the installation can provide sustainable benefits.

Previous research on the sustainability assessment of

SWPS has yet to be widely conducted, but research has been found on the assessment of sustainability aspects separately. Santra[27] evaluated the environmental aspects of solar water pumps through emission calculations and economic aspects. Economically, SWPS is cheaper than water pumps using electricity (on a grid system) and diesel, although it requires high initial installation costs. At the same time, the carbon footprint of SWPS can be ignored compared to water pumps with electricity or diesel. Hilarydoss[33] also conducted economic calculations and calculations of Greenhouse Gas emission reduction on irrigation systems in India. Haffaf et al.[34] conducted various scenarios to compare the economic and environmental aspects of several hybrid energy uses, namely PV/Battery, PV/Battery/Diesel, and Diesel generators. Dwipayana[35] measured the sustainability index of solar power plants in remote areas in Indonesia, which showed that the environmental aspect was the only aspect with a fairly sustainable status; the social and economic aspects were less sustainable. Maryati[36] conducted a sustainability assessment on all three aspects by comparing scenarios of centralized and decentralized water pump systems that still use electrical energy. Rahmani[37] measured the perception of plural communities on the social and economic needs of SWPS in Indonesia. Based on previous research, a gap in further research was obtained, namely the need for a complete assessment of the sustainability benefits of SWPS in remote areas in Indonesia.

This study aims to evaluate the benefits of sustainable SWPS installations in Indonesia, focusing on three main aspects: economic, social, and environmental. This analysis is important so that SWPS technology can be recognized, understood, and optimally implemented in various regions in Indonesia, especially areas that require environmentally friendly and energy-efficient clean water supply solutions. A comprehensive understanding of the economic impact in terms of cost savings, social benefits in improving the community's quality of life, and environmental impacts related to reducing carbon emissions will help determine whether this technology is feasible for widespread adoption or requires other more appropriate approaches.

2. Material and Methods

2.1. Solar Water Pump Systems

Solar water pumps are devices designed to draw water using energy harnessed from solar radiation, offering a sustainable alternative to conventional water pumping systems. While their physical design and installation resemble those of traditional pumps, the key distinguishing component is the incorporation of solar PV panels, which serve as the primary energy source. These panels convert sunlight into electrical energy, which is then regulated by a controller to drive the pump’s motor. The electric energy is transformed into mechanical motion, and subsequently into hydraulic energy, enabling the pump to extract water from the source.

The operational performance of a SWPS is determined by three critical parameters: pressure, flow rate, and the power supplied to the pump[23]. Variations in system configuration have been observed across different countries, tailored to specific local conditions and intended uses, as illustrated in Figure 1.

SWPS have been increasingly utilized for diverse applications such as household water supply, irrigation, aquaculture, swimming pools, and more. For small-scale irrigation, solar PV-powered systems offer a cost-competitive alternative to traditional energy sources. This advantage is expected to increase over time due to the rising cost of fossil fuels and the decreasing price of

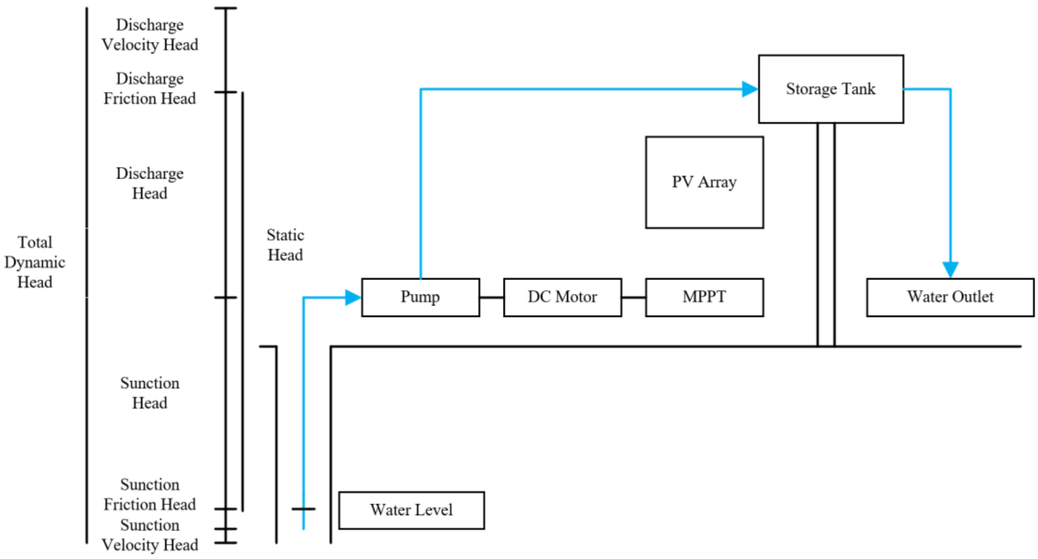

Fig. 1: Schematic of a direct coupled SWPS with MPPT[23]

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Table 1: Respondent description

No	Location	SWPS Installation	Installers	Applicators	
				Community for drinking water	Farmers for irrigation
1.	East Java	4	4	8	0
2.	West Java	5	6	5	3
3.	Yogyakarta	4	5	9	0
4.	East Kalimantan	5	5	7	0
5.	North Maluku	7	8	8	0
6.	East Nusa Tenggara	5	7	5	4
7.	West Sumatra	5	6	0	8
	Total	35	41	42	15
				98	

photovoltaic technology driven by large-scale production[38]. The integration of PV systems in off-grid water pumping has gained significant traction, especially in the agricultural and livestock sectors located in remote regions where access to grid electricity remains limited.

2.2. Methods

Primary data collection was conducted through direct surveys at 35 SWPS installations in Indonesia. Respondents consisting of SWPS installers and applicators, were surveyed from various regions, including Sumatra, Java, Kalimantan, West Nusa Tenggara, and Sulawesi (Table 1). The respondents were selected through purposive sampling, a non-probability sampling method where the researcher selects participants based on specific characteristics or their ability to provide the required data[39]. This sampling method was employed to ensure that the selected respondents would provide the necessary data to address the research objectives[40].

The determination of the sample was carried out considering that Indonesia's location is very large and data on the number or location of SWPS installations is not known with certainty. So that the aspects of affordability and availability of resources to obtain primary data are the main concerns. We collaborate with the Indonesian Clean Energy Foundation (Enerbi) and use online data from the Lorentz website (one of the producers of solar-powered water pumps/SWP) to find SWPS implementers in Indonesia.

Sampling of 35 installation with 98 respondents is in line with the guidelines described in social research with minimum of 30 respondents[41]. This has also been applied in various previous studies, such as research on the level of nutritional knowledge of adolescents[42], community health mapping[43] and ergonomic risk analysis[44], all of which used a minimum number of similar samples. In qualitative research, the selection of respondents is based on the data needs that the researcher wants to achieve[40]. The selection of respondents in qualitative research does not depend on the number of samples taken, but rather on the respondent's ability to provide in-depth and accurate information so that the data obtained can achieve a high level of accuracy[45].

Respondents in this study were classified into two main categories, namely installers who are responsible for the installation process and technical integration of SWPS, and applicators consisting of communities and farmers as direct users of the system in their daily activities. The involvement of these two groups allows for a comprehensive sustainability assessment from both the technical side and its use in the field. By combining the perspectives of technical service providers and end users, this study can describe the system's performance more completely, covering aspects of technological effectiveness, user satisfaction, and operational relevance in the local context. This inclusive approach strengthens the validity of the findings and supports the development of sustainable strategies that are oriented towards the real needs of the community in the implementation of SWPS in the future.

The survey method is used to obtain primary data. Data were collected through direct interviews and observations of the respondents. The direct survey method is used to obtain primary data by meeting directly with respondents. The procedure includes determining the purpose of the survey, compiling a questionnaire, selecting respondents with appropriate sampling techniques, conducting the survey in the field, and analyzing the data. This method provides benefits in the form of direct interaction that allows for clarification of questions, a high response rate, and richer and more accurate data. Direct surveys are also effective in areas with limited access to technology (such as remote areas that are usually for SWPS installations), making them suitable for use in various field research contexts.

Structured questionnaires were used as the primary tool for conducting the interviews. The questionnaire was based on the ISO Guide 82 - Guidelines for addressing sustainability.

Table 2: Attributes that influence the sustainability of SWPS in each dimension

No	Dimension	Attribute	Description
1.	Environment	1. Protection of biodiversity and natural resources	The installation must maintain biodiversity and not damage the surrounding natural resources.
		2. Water or air	The system must not pollute or degrade the quality of water and air in the operating environment.
		3. Pollution of land	The installation must minimize waste or contamination of the soil.
		4. Climate change	The use of the system must contribute to the reduction of greenhouse gas emissions.
		5. Energy use	The system must be efficient in its use of energy during its operation.
		6. Natural resource use	The use of natural resources in the system must be carried out wisely and sustainably.
2.	Economic	1. Value and supply chain	The system must support efficiency and increase value in the local supply chain.
		2. Technology and innovation	The installation encourages the adoption of new technologies that increase productivity and efficiency.
		3. Economic performance and development	The system has a positive impact on regional economic growth.
		4. Income	Utilization of the system contributes to increasing community income.
		5. Business	The installation opens new business opportunities in the agriculture and renewable energy sectors.
		6. Poverty	The system helps alleviate poverty through reliable water and energy provision.
		7. Employment	The implementation of the system creates direct and indirect employment opportunities in the community.
3.	Social	1. Quality of life	The system improves the quality of life of the community through better access to water.
		2. Culture	The installation must be in line with the cultural values and local practices of the community.
		3. Community involvement	Active community participation in the planning and management of the system is essential.
		4. Training and literacy	Training programs are needed to improve the technical capabilities of the community regarding the system.
		5. Education	The system can support educational activities through the provision of clean water and energy.
		6. Health and Safety	The installation must ensure safety and not endanger public health.
		7. Labor relations	The system must be managed with attention to fair and decent labor relations.
		8. Social equity	Access to the system must be equal and not cause social disparities.

Sustainability issues were extensively identified by considering the core subject structure of sustainability and related issues regarding sustainable development. The sustainability aspects in this study are based on three key dimensions from ISO Guide 82: society, the environment, and the economy. These core dimensions and the potential issues arising from their interactions are critical to the research. In implementing SWPS technology in Indonesia, each economic, social, and environmental dimension has its own supporting attributes (see Table 2).

This study's primary data analysis utilizes the Multidimensional Scaling (MDS) method, a statistical technique employed to visualize the level of similarity or dissimilarity in multivariate data through graphical representation. This method aims to map objects into a lower-dimensional space, making the relationships between objects more straightforward to understand and visualize. MDS transforms data with multiple dimensions (attributes) into a lower-dimensional space while preserving the relationships or distances between objects. Assessment using a Likert scale of 1-5 and data analysis was performed using IBM SPSS Statistics 25 software.

The sustainability status points are depicted in two dimensions: the vertical and horizontal ordinates. These points are represented by a flat line, where an extremely poor index has a value of 0%, and an excellent index has a value of 100%. The scale for the sustainability status index of the SWPS system application in Indonesia ranges from 0 to 100%. A 50% or higher score indicates sustainability, while a score below 50% suggests that the system still needs to be sustainable (see Table 3). The ordination of sustainability status provides a visualization of the

Table 3: Presents the categories of sustainability status for the SWPS application in Indonesia

No	Index	Categories
1.	≤ 24.9	Poor
2.	25 - 49.9	less sustainable
3.	50 - 74.9	Moderate sustainable
4.	> 75	Good

Source: [40]

sustainability level for each dimension based on the scores for each attribute. The index values on the x-axis represent the sustainability status of the SWPS application in Indonesia, while the y-axis shows variations in scores for the attributes studied.

3. Results and Discussion

3.1. Sustainable Benefits of SWPS Installation

Sustainability assessment in this study uses three dimensions that affect the level of sustainability in the implementation of SWPS in Indonesia. The three dimensions are economic, social, and environmental dimensions. These three dimensions are based on the initial concept of sustainability, which focuses on environmental protection, economic improvement and stability, and social acceptance by the community[46,47]. Although currently many dimensions are sustainability factors, the economic, social, and environmental dimensions are the three main dimensions used by policymakers[48,49]. Specifically related to technology implementation, several studies have also reported the use of economic, social, and environmental dimensions as influencing the sustainability of technology implementation[50,51]. In each dimension, which is a sustainability factor, attributes are used as indicators representing each dimension[52,53]. These attributes contribute as assessment indicators that will be given by respondents in each dimension[54].

The assessment of the sustainability of SWPS in Indonesia, as outlined in Table 4, reveals moderate performance across economic, social, and environmental dimensions, with an overall average sustainability index of 58.67. This finding suggests that while the implementation of SWPS is progressing, there remains substantial room for improvement to achieve a more robust and resilient sustainability profile.

A comparative analysis of sustainability scores between installers and applicators reveals a consistent pattern wherein applicators perceive higher sustainability benefits across all assessed dimensions, economic (75.30 vs. 57.26), social (58.36 vs. 50.18), and environmental (55.60 vs. 55.33). This discrepancy can be attributed primarily to the distinct roles and experiential proximity each group holds toward the SWPS technology. Applicators, who are typically end-users such as farmers or community members in rural or water-scarce areas, directly experience

Table 4: Sustainability SWPS in Indonesia

Dimension	Installers	Applicators	Average
Economic	57.26	75.30	66.28
Social	50.18	58.36	54.27
Environmental	55.33	55.60	55.47
Average	54.26	63.09	58.67

the practical benefits of the technology, such as improved water access, reduced dependency on diesel pumps, and enhanced agricultural productivity. These tangible outcomes foster a more favourable sustainability perception. In contrast, installers tend to interact with SWPS from a technical and transactional standpoint, focusing on system deployment, infrastructure logistics, and after-sales maintenance. Their lower sustainability scores may reflect exposure to systemic challenges such as high capital costs, technical constraints in remote installations, lack of ongoing technical support, and policy uncertainties. Furthermore, applicators often benefit from government or donor-funded installations, reducing their financial burden, while installers bear the complexity of coordinating supply chains and addressing site-specific technical variances. This divergence suggests the need for policy and programmatic alignment that not only supports the end-user but also strengthens the enabling environment and capacity for local installers, ensuring both groups perceive, and experience sustainability gains more equitably.

From an economic standpoint, the sustainability score averaged 66.28, with applicators reporting a significantly higher score (75.30) compared to installers (57.26). This disparity indicates that applicators, who are typically end-users or local stakeholders directly engaged with the daily operation of the SWPS perceive greater economic benefits, such as cost savings on fuel and reduced labour burden, consistent with findings by Renjini *et al.* (2020), who observed enhanced economic viability of solar-powered irrigation systems among smallholders in India[55]. The relatively lower economic score among installers may reflect challenges in procurement logistics, initial capital cost, or limitations in market access, which are also noted as key barriers to solar technology diffusion in rural contexts[56].

Some SWPS installations in Indonesia are assistance from the central or regional government, allowing users to provide a little capital, only to do maintenance. However, there are also SWPS that are installed using community contributions. Although the initial costs are quite large, they get the appropriate benefits. Implementation of SWPS technology provide greater benefits for applicators (community and farmers), especially for remote areas that experience water resource difficulties[54]. Some areas in Indonesia are included in areas experiencing water shortages because there are no facilities or technologies that can be used to distribute water from its source to residential areas. In addition, other studies also report that the use of SWPS provides competitive economic benefits compared to conventional methods, so the use of SWPS is recommended in the provision of water resources[54].

Social sustainability scored the lowest among the three dimensions, with an average of 54.27. This may reflect constraints in culture, community engagement, knowledge transfer, and institutional support. Although applicators again rated the systems slightly higher than installers (58.36 vs. 50.18), the scores suggest a need for stronger social embedding of the technology. Social acceptance and capacity-building have been cited as critical determinants for the long-term success of decentralized renewable energy systems[57]. When SWPS users benefit from this installation, they feel that their lives are helped, which makes their social life better. Ensuring adequate training, stakeholder involvement, and equitable benefit-sharing could enhance the perceived and actual social value of SWPS.

Socially, the implementation of SWPS certainly requires specific expertise in its operation, which will have a social impact on the community that will utilize it. Therefore, to maintain the sustainability of the implementation of SWPS technology, it is necessary to distribute operational knowledge of SWPS to the community so that the community will also be involved and have the technology that is applied[58]. Providing sufficient water resources in remote areas will bring about better social change because the need for water as a basic human need can be met.

In contrast, environmental sustainability was found to be relatively stable across groups, with nearly identical scores between installers (55.33) and applicators (55.60), resulting in a consolidated average of 55.47. These scores indicate a moderate level of environmental benefit realization, aligning with expectations given the inherent low-emission and non-polluting nature of solar water pumping. However, the relatively modest scores may also reflect concerns about lifecycle impacts, such as photovoltaic panel disposal, or land-use considerations[59]. Further improvement in environmental sustainability may be achieved through circular approaches and sustainable procurement strategies for solar components.

Environmentally, implementing SWPS can reduce environmental impacts, especially greenhouse gas emissions. Using SWPS to provide water resources can reduce GHG emissions compared to fossil energy sources, such as electricity from the grid with coal fuel[33]. The use of coal as a fuel in producing electricity will produce an average of greenhouse gas emissions of 1432 g CO_{2eq} for 1 kWh, while the use of solar-based energy sources produces almost no emissions[60]. So, using SWPS as an alternative technology based on new and renewable energy is highly recommended because it can protect the earth from global warming due to greenhouse gas emissions.

While the overall sustainability index (58.67) suggests that SWPS in Indonesia is progressing toward viability, a more integrative strategy is necessary to elevate its sustainability, especially in social dimensions. Policy interventions should emphasize not only infrastructure deployment but also institutional readiness, participatory frameworks, and localized innovation. Future work may integrate longitudinal assessments or participatory scenario modelling to capture evolving sustainability dynamics and stakeholder perspectives over time.

3.2. Discussion of Economic Dimensions

As previously explained, the sustainability value of the solar water pump system, or SWPS, is necessary to evaluate it economically. In this study, the comparison of Figure 1 shows that the economic dimension variable has the highest value (66.28) compared to the social and environmental dimensions. This means that respondents have the highest confidence in implementing SWPS for its economic impacts compared to other dimensions.

From the questionnaire given to respondents, the economic impacts referred to are in the form of (1) potential for job creation, (2) poverty reduction, (3) business creation opportunities, (4) providing benefits and income, (5) community economic development, (6) triggers for technology and innovation development, and (7) providing added value along the water supply chain. The scores for each economic dimension variable shown in Figure 2 show that the highest value is for technology and innovation, followed by added value along the water supply chain and job creation. Meanwhile, other economic dimension variables have relatively identical scores or are considered no different.

The graph in Figure 2 dan 3 can be interpreted as indicating that the implementation of SWPS triggers technology and innovation along the water supply chain, resulting in the opening of new jobs (Figure 4). Figure 4 shows that initiating innovation and technology is like new business opportunities that provide profitable activities. With that, new jobs are created, providing income and alleviating poverty, are provided. The effect along the supply chain creates the macroeconomic development of the community. The findings obtained in this study align with existing scientific article publications discussing the benefits of SWPS implementation in the context of rural areas and isolated areas.

The community's macro economy improves with the application of SWPS in helping to provide water as a basic human need[61]. The justification for climate change mitigation is commonly used to make changes from diesel to solar power. However, SWPS can further trigger development and reduce vulnerability and resilience in farmers or residents with food security. Furthermore, regarding benefits, SWPS has the most significant additional benefits for farmers, such as reducing irrigation and labour costs[62]. Reducing labour with SWPS is possible because its operation does not need to be supervised. About 35% of the 150 SWPS in Bangladesh are used for irrigation, and the remaining 65% are used to provide drinking water for people experiencing poverty. Solar PV-powered irrigation pumps increase crop yields and intensify agriculture[63].

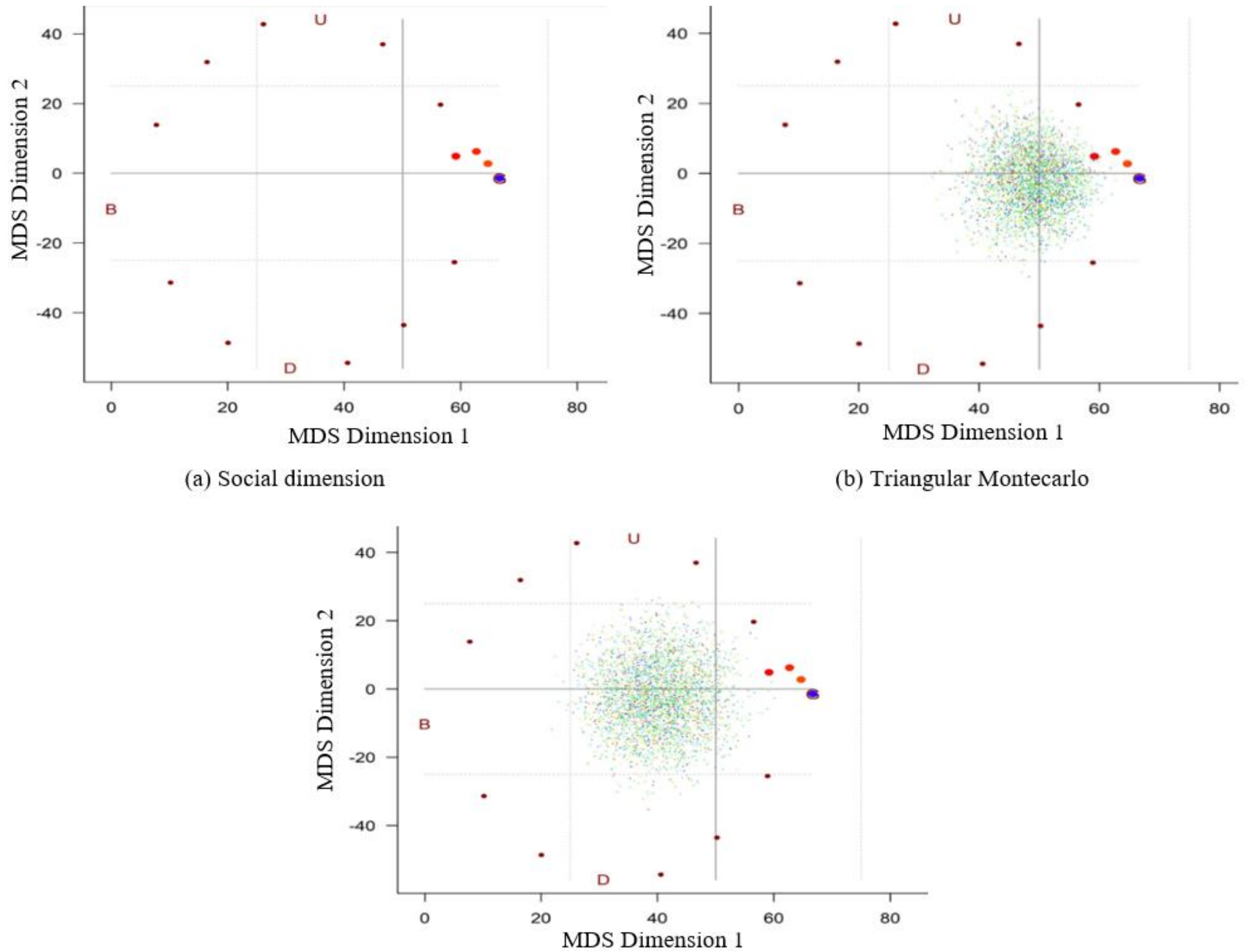


Fig. 2: Sustainability of SWPS in the economic dimension

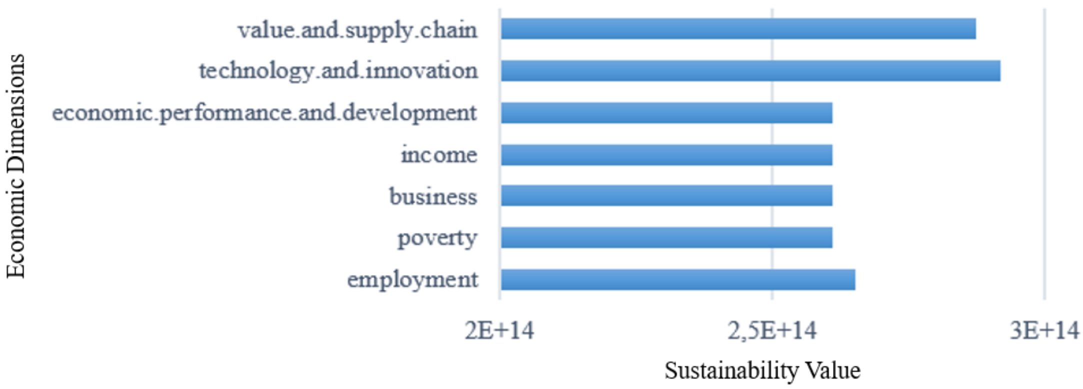


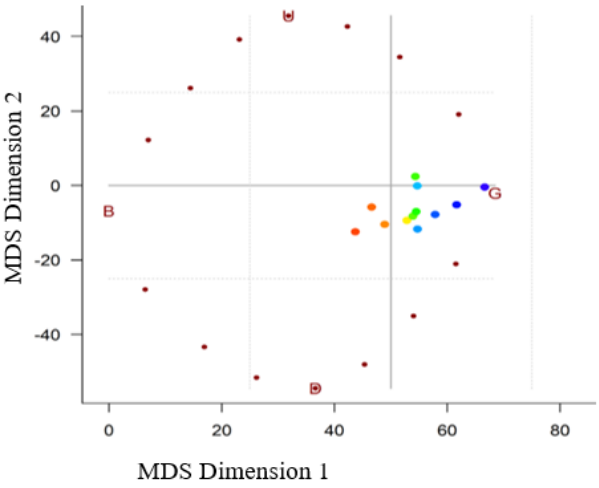
Fig. 3: The influence of each economic dimension variable on SWPS sustainability

Fig. 4: Interpretation of the impact of the economic dimensions of SWPS

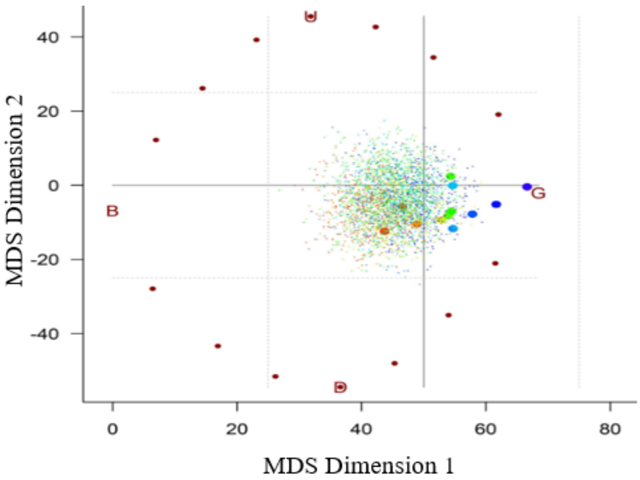
3.3. Discussion of Social Dimensions

In the questionnaire related to the social dimension, eight social dimension indicators are measured: quality of life, culture, community involvement, training and literacy, education, health and safety, labour relations, and social equity. All thirty-five respondents provided complete responses regarding these social dimension indicators. The social sustainability measurement of SWPS in Indonesia shows it is sustainable (Figure 5 and 6). With a sustainability index score of 54.27, the social impact of SWPS is felt through community involvement. Each SWPS installation that operates creates at least two jobs. Most farmers are also satisfied with the SWPS installation for their irrigation needs[64]. SWPS The sustainability of SWPS functionality is also closely tied to community involvement. SWPS installation requires large capital and is usually capital from the entire community. When they benefit from this program, they will feel like they own it and take good care of it. Social capital facilitates collective action in society and has a positive impact on the protection of SWPS utilization[65].

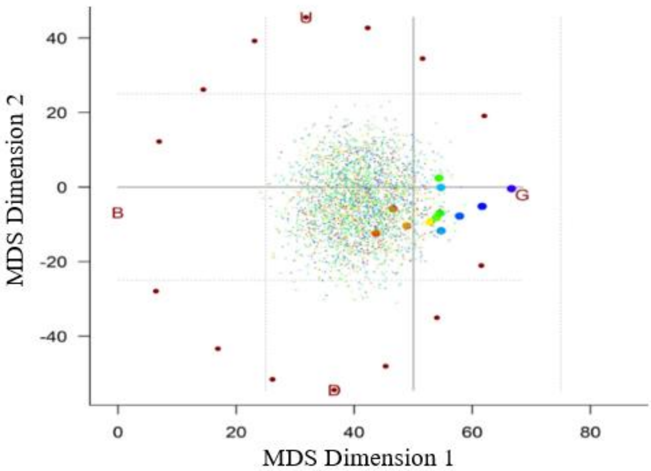
A lack of knowledge transfer, unclear instructions, and insufficient organization systems between SWPS providers and the community can affect the continued functionality of SWPS[64]. Involving the local community in the management of SWPS will at least enhance their capacity in water distribution management, SWPS maintenance, operational, financial management, and communication skills with water users and external parties[64]. In implementing SWPS, the village government usually has a strong influence, while higher-level governments are less influential. As a result, the local community tends to communicate more intensively with village officials. Social aspects play an important role in the development and application of technology[66].



(a) Social dimension



(b) Triangular Montecarlo



(c) Uniform Montecarlo

Fig. 5: Sustainability of SWPS in the social dimension

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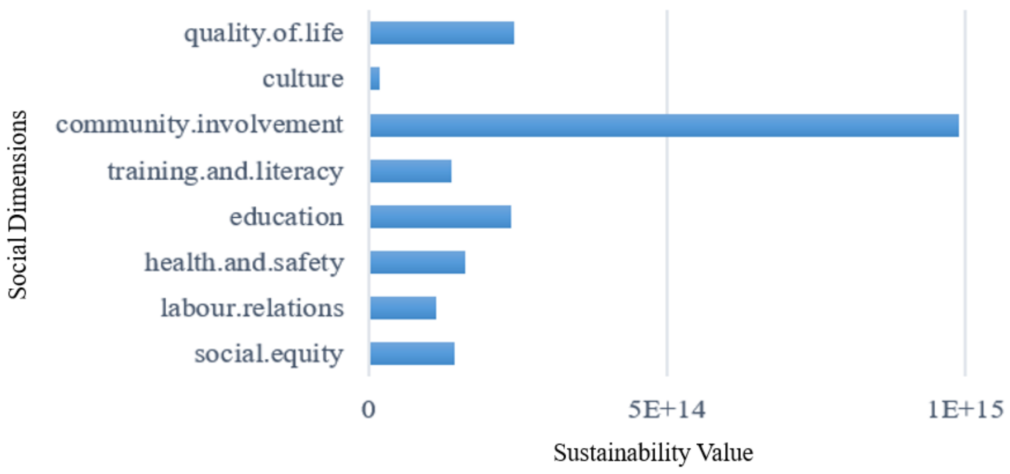


Fig. 6: The influence of each social dimension variable on SWPS sustainability

The interpretation of Figure 7 also shows that, of the eight indicators in the social sustainability dimension, culture does less influence the sustainability of SWPS in Indonesia. Cultural aspects might affect the adoption of off-grid renewable energy[67]. Culture can help address barriers to renewable energy penetration by managing conflict and encouraging community participation[68].

3.4. Discussion of Environmental Dimensions

The solar-powered water pump is an economical and environmentally friendly technology ideal for farmers, horticulture, and remote rural areas that struggle to access clean water[69]. This water pump operates without electricity from the power grid[70]. In a SWPS, sunlight is converted into electricity to pump water, which can then be distributed through pipes to a communal reservoir using a gravity system, allowing nearby residents to use the water for daily needs. Therefore, several factors must be considered when designing a solar-powered water pump, including solar flux, local water demand, water storage size, water table depth at the location, pump flow rate, panel size, and more[71].

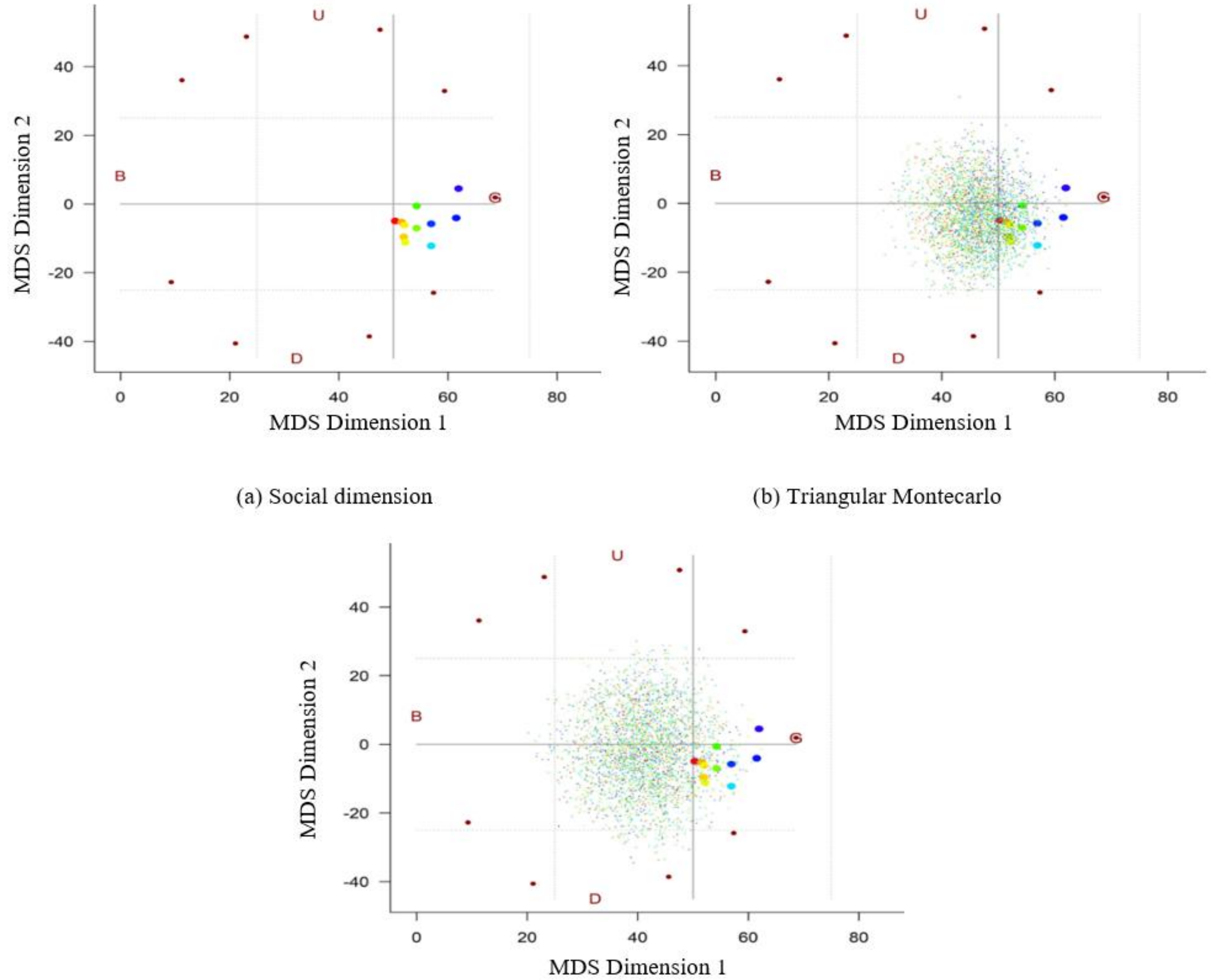
This research provides information that, from an environmental perspective (Figure 7 and 8), it will be possible to support the development, operation, or use of solar-powered water pump installations, making them sustainable in Indonesia. The utilization of solar energy available year-round in Indonesia plays a key role in the operation of these installations. Solar energy use is considered carbon-neutral, helping reduce anthropogenic CO_2 emissions globally[71]. The solar energy system does not produce air or water pollution. Solar energy can indirectly positively impact the environment when it replaces or reduces the use of other energy sources with a more significant environmental impact, thereby contributing to environmental preservation[72].

Installing water pumps powered by solar energy to replace fossil fuels can drastically reduce greenhouse gas emissions, especially carbon dioxide (CO_2). Greenhouse gases, produced when fossil fuels are burned, contribute to global temperature increases and climate change. Climate change has led to environmental issues, including extreme weather events, rising sea levels, and ecosystem shifts. Solar energy can reduce fossil fuel demand, limit greenhouse gas emissions, and minimize carbon footprint[70].

Establishing a solar-powered water pump installation must consider the land and ecosystem at the local site. Key considerations in setting up such an installation include using land not designated as productive, thereby avoiding disruption to biodiversity and natural habitats (Figure 8). One option is to develop unused land near plantations, farms, or rural areas with minimal tree coverage, allowing solar energy to be directly captured by solar panels without shading. Alternatively, ground cover under the panels can be enhanced to minimize negative impacts on biodiversity and natural habitats or riparian zones planted. When combined with such approaches, the installation can preserve biodiversity at the site as long as extensive tree and shrub areas are not cleared in the process[73]. Environmental sustainability is an important aspect of human development[74].

Sustainability assessment of SWPS shows that this technology has significant potential in supporting the transition to a more environmentally friendly and efficient water supply system. From an economic perspective, SWPS offers advantages in the form of lower operational costs and shorter payback periods compared to fossil fuel-based pumps, such as diesel pumps[75,76]. On the technical side, this system has been proven to show good performance and reliability, even in some cases exceeding initial design expectations[77]. This makes SWPS a reliable solution, especially in remote areas that have limited access to conventional energy infrastructure.

However, the long-term sustainability of this system is not only determined by technical performance alone, but is also influenced by various other interrelated factors, including environmental, financial, and institutional support dimensions[78]. In this context, the existence of external support from solar PV technology experts and local stakeholders is very crucial to ensure the continuity of system operations and maintenance in the long term[79]. In addition, from an environmental perspective, SWPS provides positive contributions in the form of reduced carbon emissions, reduced need for periodic maintenance, and a relatively longer system life compared to conventional diesel pumps[80].



(a) Social dimension

(b) Triangular Montecarlo

(c) Uniform Montecarlo

Fig. 7: Sustainability of SWPS in the environmental dimension

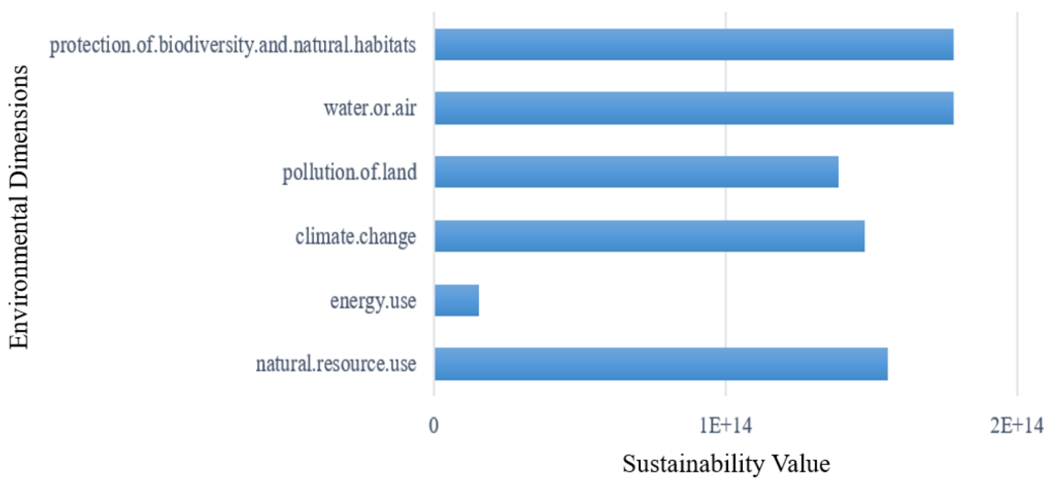


Fig. 8: The influence of each environmental dimension variable on SWPS sustainability

3.5. Practical Implication, limitation, and future research agenda

3.5.1. Practical Implication

The study's findings on the economic benefits of SWPS, which include cost savings and energy efficiency, may motivate governments to provide subsidies or tax incentives to speed the adoption of the technology, particularly in rural areas that do not have access to clean water. The incorporation of SWPS projects into development initiatives aimed at water-deficient regions is something that both governmental and non-governmental organizations can accomplish. It is also important to note that SWPS has the potential to contribute to the enhancement of the quality of life in communities such as fulfillment of primary human needs for water, improving health, reducing costs and the number of workers in water collection. In addition, the environmental benefits, including a reduction in carbon emissions, highlight the importance of promoting renewable energy sources for water supply. This contributes to the actualization of Indonesia's national objective of lowering emissions of greenhouse gases. In the end, this study provides a framework that can be repeated across several locations, which enables modification to the specific requirements of the places and the available resources. This may make it easier for more people nationwide to embrace environmentally friendly, sustainable water supply systems. Sustainable aspects are an important factor for the development and use of SWPS technology in the long term[81]. Promoting green energy initiatives is essential to meet energy demand and provide sustainable living[82].

3.5.2. Limitation

For this study, the entire territory of Indonesia is not covered. Because of this, the conclusions obtained might be specific to a particular site and might not apply to other locations with distinct socio-economic or geographical characteristics. In addition, the availability of economic, social, and environmental data can influence the accuracy of the SWPS sustainability evaluation. Furthermore, the research needs to consider the possibility of future technological advancements in water supply or renewable energy systems. Both factors can impact the overall viability and sustainability of the SWPS in the long term. Even though it focuses on the social element, this study needs to capture adoption's behavioral aspects adequately. For example, the system's acceptability by local communities needs to be considered, and the difficulties of maintaining it over the term. For the SWPS deployment to be successful, these factors are necessary. This study uses sustainability aspects in ISO Guide 82 - Guidelines for addressing sustainability, so that future research can be conducted by adding other aspects, including quantitative aspects (e.g., carbon offset, water efficiency, life-cycle emissions).

3.5.3. Future research agenda

There is the potential for a study to be carried out to analyze the long-term implications of the economic, social, and environmental impacts that SWPS installations have over time. This would offer a more comprehensive perspective on the concept of sustainability. Furthermore, if this research were expanded to include different geographical places in Indonesia, each with a different climate and social environment, it would provide helpful information on the adaptation of SWPS programs by including these locales. Through research on integrating SWPS with other renewable technologies (such as solar energy storage systems), it is possible to identify ways to enhance efficiency, reduce costs, and mitigate the environmental impact. Aspects of operational reliability, maintenance challenges, or seasonal variability in solar irradiance are also interesting research aspects for the future. In addition, the application aspect of Blockchain and Internet of Things in SWPS is also research that is in line with advances in science and technology[83].

To carry out additional research on social effects, it is possible to carry out a study on the role that community engagement plays in the accomplishment of SWPS activities. This inquiry may concentrate on the significance of education and local capacity development to guarantee the continuity of system maintenance and resilience. Since the policies of the government regarding renewable energy and water management continue to develop, future research might study how the scalability of SWPS technologies and the adoption rates of these technologies are affected by variations in rules and incentives. SWPS equipment in Indonesia is mostly imported and the price is still expensive for use in remote areas. Policies for taxes and incentives for system applications will be interesting in expanding the application of this system.

4. Conclusions

The sustainability assessment of SWPS in Indonesia indicates a moderately sustainable performance across economic, social, and environmental dimensions, with an overall index of 58.67. Economically, SWPS demonstrates promising benefits, especially for applicators such as farmers and local communities who report tangible gains in operational cost savings and access to water, despite persistent challenges in capital investment and system deployment experienced by installers. Social sustainability, however, emerges as the most critical area for improvement, reflecting cultural changes and differences, limited community engagement, knowledge dissemination, and institutional support for training and literacy. Enhancing social acceptance and capacity building efforts is essential to foster broader community involvement and long-term system viability. Environmentally, SWPS offers a relatively stable and low-emission solution to water access in rural areas, aligning with global efforts to reduce carbon footprints, though concerns about lifecycle management and land use remain. Taken together, these findings underscore the need for a more integrated and inclusive implementation strategy that not only prioritizes technology deployment but also addresses socio-institutional dynamics and sustainability awareness. To strengthen the future trajectory of SWPS, policy efforts must be grounded in participatory approaches, targeted training, and adaptive innovation that align with local contexts and long-term environmental goals.

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