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Pin, Lantos A.; Pennink, Bartjan J.W.; Balsters, Herman; Sianipar, Corinthias P.M.

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Technological appropriateness of biomass production in rural settings: Addressing water hyacinths (*E. crassipes*) problem in Lake Tondano, Indonesia

Lantos A. Pin [a], Bartjan J.W. Pennink [b,e], Herman Balsters [a], Corinthias P.M. Sianipar [c,d,*]

[a] *Department of Operations, University of Groningen, Nettelbosje 2, 9747 AE, Groningen, the Netherlands*
[b] *Department of Global Economics and Management, University of Groningen, Nettelbosje 2, 9747 AE, Groningen, the Netherlands*
[c] *Division of Environmental Science and Technology, Kyoto University, Kitashirakawa Oiwakecho, Sakyo Ward, Kyoto 606-8502, Japan*
[d] *School of Business and Management (SBM), The Bandung Institute of Technology (ITB), Jl. Ganeca 10, Bandung, West Java 40132, Indonesia*
[e] *The Institute of Finance Management (IFM), 5 Shaaban Robert Street, Dar Es Salaam 11101, Tanzania*

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ABSTRACT

Climate change has induced an excessive growth of water hyacinths, which produces unintended consequences for the surrounding ecosystem. Particularly, water hyacinth is a major problem throughout the world's tropical zone, which largely consists of rural regions. One way to address the water hyacinths problem is to convert them into biomass. However, typical biomass production technologies have not considered local settings when they are installed in rural areas lacking knowledge and resources. This study aims at assessing the technological appropriateness of biomass production from water hyacinths in rural settings under limited resources and knowledge. This research proposes two scenarios (*i.e.*, high-tech and low-tech) to utilise water hyacinths from Lake Tondano, Indonesia, as the case study. The scenarios consider local settings of communities living around the lake by applying scenario-based design science according to Weiringa's adaptation of the five-stage regulative cycle of Van Strien. The assessment stage employs three levels of technological appropriateness (techno-economic, environmental, social) to assess each scenario for the rural context. Results show that the low-tech design is more appropriate for rural settings around Lake Tondano. Both designs are technically able to resolve the water hyacinths problem; however, the low-tech design is more practical for local communities, addressing the environmental problem while simultaneously boosting socioeconomic developments. In general, the small-scale nature of the more appropriate design applies to other rural areas, with which those areas can utilise various biomass sources while benefitting their socioeconomic situations. Further studies need to assess the technological appropriateness of the appropriate design again based on rural contexts in their location(s).

1. Introduction

Climate change is consistently pushing the upper boundary of global temperature to a new high. In general, the increasing temperature occurs all over the world [1,2], gradually making every spot in the world warmer. It has been widely referred to as bringing negative consequences, which include the dramatic increase of manmade disasters [3,4], the decreased liveability of our oceans [5,6], the heightened risks of food security [7,8], the tightened scarcities of drinking water [9,10], *etc*. Practically, the undesirable consequences of climate change affect the different facets of biological and social systems either directly or indirectly. Climate change typically delivers negative impacts to parts of biological and/or social systems directly albeit in different periods [11,12]. The impacts of climate change eventually disrupt the stability of affected systems, which could reduce their capacity to maintain long-term balances in the nature or society. As an example, climate change-induced shifts of seasonal temperature fluctuation alter the agriculture timetable [13–15], which would reduce yields and eventually affect food security. At times, however, the effects of climate change may occur first as positive impacts to certain parts of biological systems, yet it would later lead to negative impacts to different system parts connected to the first-affected parts [16–18]. For instance, a warmer temperature may lead to better growth circumstance for certain plants, yet the changing state might later cause an imbalance of food chains

* Corresponding author. Division of Environmental Science and Technology, Kyoto University, Kitashirakawa Oiwakecho, Sakyo Ward, Kyoto 606-8502, Japan.
E-mail addresses: b.j.w.pennink@rug.nl (B.J.W. Pennink), h.balsters@rug.nl (H. Balsters), iam@cpmsianipar.com, cpm.sianipar@gmail.com (C.P.M. Sianipar).

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and/or natural cycles of plant lives due to an excessive growth that goes beyond the natural provision of growth medium and nutrition [19–21].

An interesting example of a situation as such appears in the environmental issue brought by water hyacinths (*E. crassipes*) [22–24]. Biologically speaking, it is a free-floating and rapidly growing perennial aquatic plant, which has technically been known for its applications in various efforts of water quality improvements [25,26]. In fact, the warmer temperature induced by climate change has produced a much better circumstance for the plants to grow. In that sense, climate change delivers a positive impact on the growth of water hyacinths, which, however, results in an excessive growth [27,28]. In particular, the sunlight- and nutrient-rich water available in numerous lakes and waterways throughout the tropical zone have further supported the excessive growth of water hyacinth, making it a major problem to regions around the equator [22–24]. As a direct consequence, the excessively growing plants are covering wider surfaces of water bodies, including ponds, lakes, *etc*. The plants then consume much dissolved oxygen (DO), reducing oxygen availability for other water creatures such as fishes and other aquatic plants [29–31]. Besides, decaying water hyacinths have long been known to consume a much higher amount of oxygen than when they are still alive [32,33]. Indirectly, the excessive growth of water hyacinths leads to reduced yields of fishes for human consumption, which would later affect he economic situations of fishermen, and weaken the food security of rural communities around the water body [34,35]. Besides, it would impact social situations in communities living around the water bodies due to, for instance, decreased job opportunities that would eventually result in increased unemployment.

In the literature, water hyacinth is known to contain an incredibly high moisture content of around 90% [36]. Studies have recognised it as a viable source of bioenergy in the form of biomass [32,37,38]. The types of biomass sources are woody plants (1), herbaceous plants/grasses (2), aquatic plants (3), and (4) manures [39]. Water hyacinths thus fall into the second category. To solve the water hyacinths problem, researchers have thus come up with a proposal to convert them into biomass. In the last decade, research works on the conversion of water hyacinths into biomass have resulted in the development of various technologies. However, the efforts have rarely considered beyond technical functions of biomass production technologies [40–42,141]. To a limited extent, economic considerations have been considered [32,43], yet they are tied to the values of technologies and have not covered less developed economic situations, let alone constrained social conditions [44,45], of users of the technologies. Considering the typical locations of water hyacinths sources in tropical water bodies surrounded by rural areas, the technological appropriateness of biomass production technologies is becoming more critical due to the lack of knowledge and limited resources available. Practically, proper technological appropriateness [46,47] would ensure an impactful application of biomass production technology to the rural communities living around water hyacinths-occupied water bodies, leading to sustainable utilisation of water hyacinths and improved socioeconomic situations of the communities. Therefore, this study aims at analysing the technological appropriateness of biomass production technology in rural settings. To understand the technological appropriateness of different water hyacinths conversion technologies in the same rural settings, this study employs scenario analysis. This study hence attempts to address the following research questions:

Q1. How biomass production technology from water hyacinths can affect or be affected by rural settings?

Q2. What technological design scenarios may occur from a situation as such?

Q3. How those scenarios are assessed for their technological appropriateness in the local (rural) context?

2. Literature review

2.1. Water hyacinths and issues in biomass production

Sustaining the utilisation of water hyacinths as a biomass source must ensure the delivery of an optimum result of the whole bioenergy conversion process [41,48]. Therefore, the utilisation must first consider the major characteristics of water hyacinths. Converting water hyacinths into biomass offers highly advantageous by-/products, including organic fertiliser from the solid mass of the plants, and bioenergy from biomass feedstocks of the plants [32,39,49]. Organic fertiliser produced from water hyacinths would, in comparison to other fertilisers, better improve the yield of different crops due to its high concentration of nutrients [32,50,51]. In short, water hyacinth can be a source of important nutrients for farmlands. As the domino effects, it would enhance the quality of agricultural products, ensuring stronger food security, providing adequate nutrition, and eventually improving the livelihoods of farmers [43,48,52]. Water hyacinths can therewith serve as an option to both meeting the ever-growing energy demand and sustainably supplying an organic fertiliser. When the biomass production process occurs in rural settings, the areas, communities living around a water hyacinth site, and the agriculture sector could expect benefits from the conversion process. However, a technically minded energy generation as such requires extensive investments and technological skills [32,53–56], making further burdens to rural people due to lacking economic resources [57,58,141] and limited technical knowledge available [59,60,141]. Furthermore, applying the AD technique to address the water hyacinths problem implies crucial considerations of how the whole conversion process and the products (organic fertiliser and bioenergy) are flown and distributed from their source(s) to their designated end-users. Thus, bioenergy production raises concerns on supply chain management issues and streamlined logistics activities [49,61–64]. In its practices, the management of a supply chain focuses on the integration of all intermediate entities to ensure the production and distribution of a final product in the right quantity, at the right time, to the right location, for fulfilling desired quality and service levels, and to minimise the overall cost of product being delivered [65–67]. A supply chain performs according to the degree of integration and harmonization between involved entities, which goes along with an efficient downstream flow of products and an upstream flow of information [68,69]. In contrast to manufacturing supply chains, which must deal with demand uncertainties [70,71], a Biomass Supply Chain (BSC) must deal with supply uncertainty [49,72,73]. Utilising water hyacinths as a biomass source has the exact problem due to the variability of growth of the plant [62], making it more problematic when a BSC begins with rural settings lacking resources and technical knowledge. Consequently, multiple decisions concerning a BSC must be made [49,62,74,75]. The complex nature of these decisions shall lead to a thoughtfully feasible and sustainable BSC [63].

2.2. Technology appropriateness in Biomass Supply Chain

However, the construct of sustainability perspectives of BSC considerably leans to a Western-leaning perspective where technological and economic mindsets differ significantly from rural people in the context of developing economies [76–78]. It is compounded by inherited issues from choices of controlling the excessive growth of water hyacinths. Besides physical control [79], other efforts include biological (*e.g.*, water hyacinths-eating insects, growth inhibitor, *etc*. [80,81]) and chemical (*e.g.*, pesticides, *etc*. [82,83]) treatments, yet they may not be desirable in rural settings because they often are ineffective, possibly prohibited, or simply not feasible in constrained rural circumstances. To overcome critical issues as such, establishing BSC in a rural context must consider the appropriateness of biomass production technologies applied in certain stages of the BSC, ensuring the impacts of the critical process(es) within the supply chain to communities living around a biomass source [78,84]. Particularly, designing BSC in a rural context shall consider the technological appropriateness at three different tiers, which include basic, environmental, and social appropriateness [58,85]. These tiers shall ensure the correct diffusion of a technology (or a set of technologies) into the community's routines and guarantee its sustainability [86,87]. The first tier (basically appropriate) incorporates the most tangible aspects of any technology, which are its techno-economic aspects [57,58,88,89]. Meanwhile, the second tier puts a further concern on environmental aspects [46,47,58], whereas intangible social aspects [45,46,58] are considered in the third tier. In that sense, understandings covered in these tiers closely relate to theories on Local Economic Development (LED) [85,90,91]. Therefore, the three tiers of technological appropriateness may theoretically be stated as a holistic understanding to pursue a sustainable state of technology application in BSC-driven LED effort from multiple perspectives (technical, economic, environmental, social). The pursuit of technological appropriateness of biomass production technologies in BSC shall then include considerations from rural stakeholders [45,92,93]. The combined perspective then represents the interests of those actors in aiming at an ultimate, if not sole, goal for improving local conditions [46,58,93–95]. As the result, ensuring technological appropriateness in rural BSC can produce a competitive biomass production and strengthen the sustainable development of the rural area. In that sense, ensuring technological appropriateness would require careful considerations during the design process of technologies applied in the BSC. While most biomass production technologies exist as given by their manufacturers, the issue in question moves to ensuring the technological appropriateness when the technologies are going to be introduced into the rural BSC. Therefore, the assessment of technological appropriateness would be a miss-and-match between characteristics of the given technologies to the rural settings they would be installed in.

2.3. Research positioning and framework

In general, two flows relate to the focus of this study. The first one is Biomass Supply Chain (Fig. 1; upper part). Structurally, BSC consists of the harvesting of biomass source(s), storage [96,97], pre-treatments [98,99], storage [74,100], and energy conversion [101,102]. Transportation and handling [96,103,104] are required in-field after harvesting, and between other discrete processes to the downstream direction. Considering the focus of this research on rural context lacking resources and knowledge [45,58,60] to conduct a sustainable and scalable energy conversion (bioenergy production) process, which could require intensive investments and advanced technical knowledge, this research chooses to target the pre-treatment stage. Typically, the biomass pre-treatment stage consists of discrete and reciprocal sub-activities: processing and conditioning. The processing activity is designed to improve the transportation and storage characteristics of biomass, while the conditioning activity aims at influencing its biological characteristics, including moisture content [105]. As an intermediate process between biomass harvesting/supply and bioenergy conversion, the pre-treatment stage is critical in preparing harvested biomass source(s) into a suitable form for bioenergy production at a designated energy conversion facility [106]. Thus, targeting the pre-treatment process in rural contexts would imply the higher importance of assessing technological appropriateness to ensure both suitable technical specifications of the biomass for the designated bioenergy production and the benefits of biomass production for the rural area and communities living around the biomass source(s).

Meanwhile, the second flow is the technology design (Fig. 1; lower part). Starting from local (rural) context as the fundamental basis of technological appropriateness [86,107], the technology design flow covers four stages: Planning, Concepting, Designing, and Assessing. To deliver a strong focus on the technological appropriateness of biomass production (pre-treatment) technology, this research partially covers Designing and Assessing stages. In the Designing stage, two scenarios (*i.e.*, high-tech and low-tech) are introduced. This study does not focus on detailed and technical design processes since they are not included in the problem statement of this research. Thus, the technological scenarios being introduced are given, by which the design process can solely focus on discovering the techno-economic, environmental, and social characteristics of each scenario. Information for the Designing stage come from the target process (pre-treatment), while outgoing information refer to inputs/references for the Assessing stage. In this stage, this study covers Valuation, Evaluation, and Judgement/Decision-making sub--stages; however, in this case, the partial coverage of the stage does not cover protocols for technical testing of each technology. Instead, this research focuses on assessing the technological appropriateness of each

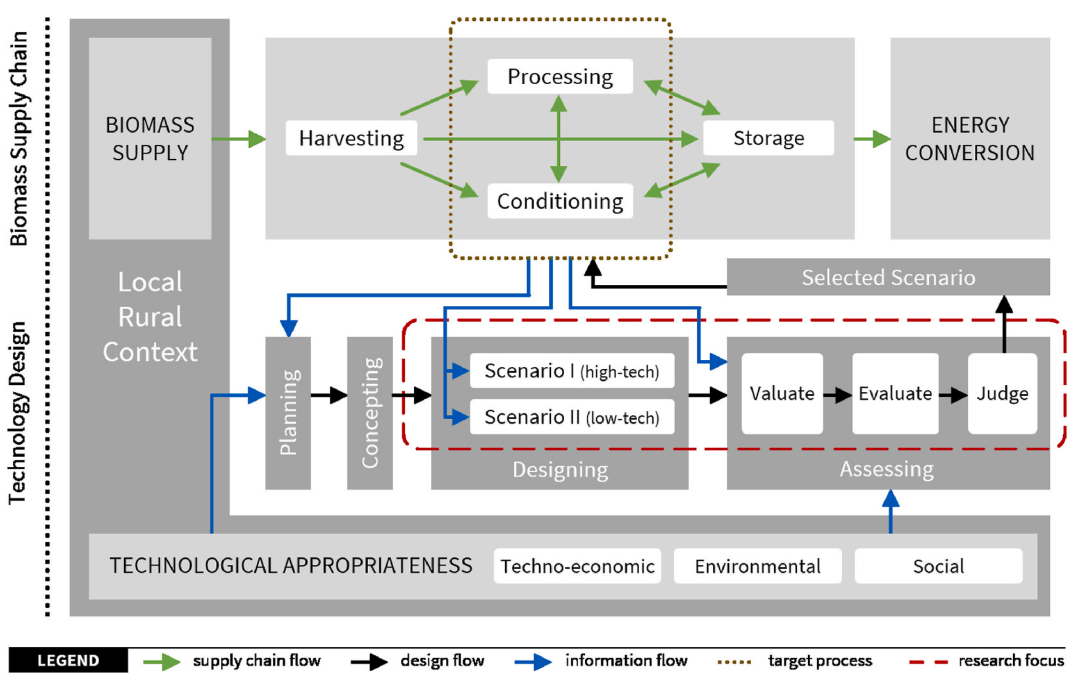


Fig. 1. Research positioning and framework.

scenario by matching its characteristics, including given technical performances, to the local rural context. Input information come from the Designing stage and the targeted biomass production process (pre--treatment). In the end, the Assessing reveals which scenario has higher technological appropriateness for the rural settings it is located in. The selected technology implies the most appropriate scenario for the target process (pre-treatment).

3. Methodology

3.1. Research design

The research framework established above and the second (Q2) as well as third research questions (Q3) relate, by definition of Wieringa [108,109], to a practical problem for which the scenario-based design science is applied. The research approach applied in this study is based on the five-stage regulative cycle of Van Strien [110] (Fig. 2). Later, Wieringa [108] has adapted it to report the results of a design science study in an organised manner. As this research addresses the problem of technological appropriateness of scenarios in question, the research stage shall begin from a problem investigation of the solutions being observed. However, this research intends to end with the assessment of the technological appropriateness of given technological scenarios, implying that this study does not cover technical implementation and post-implementation evaluation. Considering these arguments and the positioning and framework of this research (Fig. 1), the design of this study is built upon the first three stages of the adapted regulative cycle. In detail, the Problem Investigation stage focuses on the investigation of the local rural context, and the techno-economic, environmental as well as social characteristics of each proposed scenario. In design science studies, rural stakeholders shall formulate specific goals and functional and non-functional critical success factors from which detailed quality attributes (QAs) can be formulated. However, the lack of resources and limited availability of knowledge in rural contexts may make rural stakeholders unable to be specific regarding the QAs. As the result, this study takes inputs from the stakeholders as perspectives by which three general sets of QAs are formulated. Each set corresponds with one of the three tiers of technological appropriateness [85] to ensure a correct

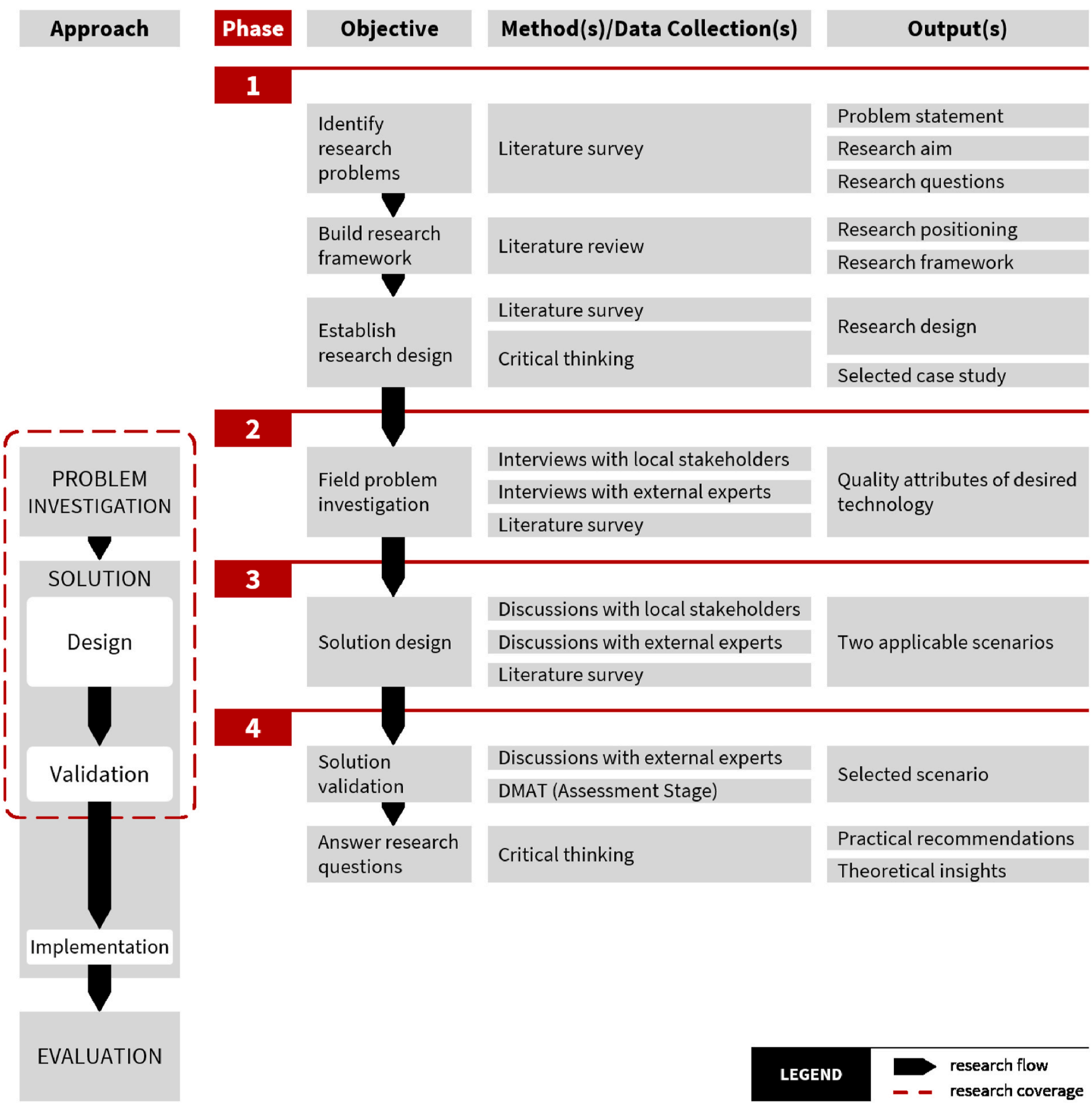
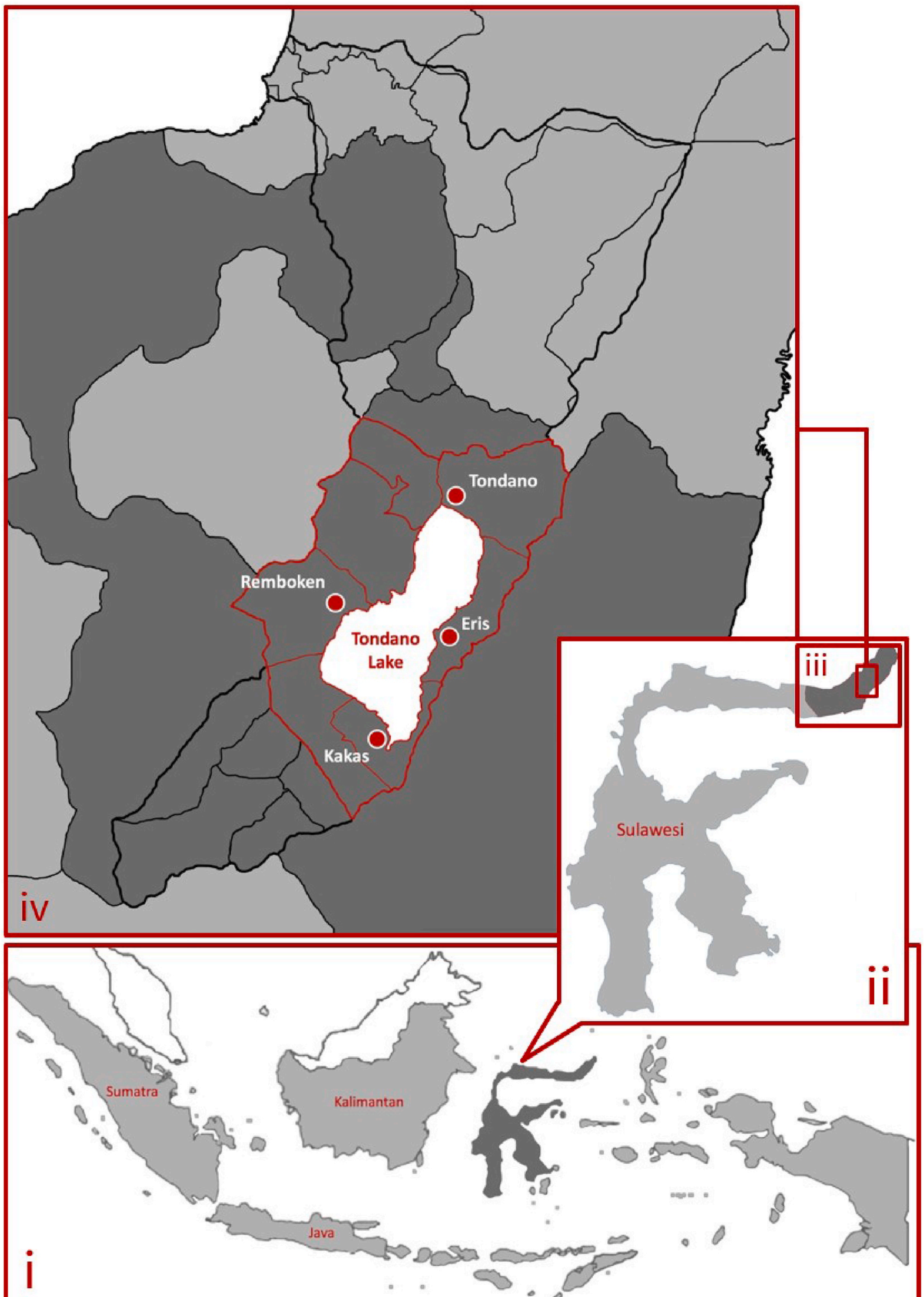


Fig. 2. Research approach and design.

diffusion of the proposed technological scenario into the community's routines [86,87]. The data collection techniques include interviews with local and external experts, and a literature survey. In the Solution Design stage, this study discovers the given technological scenarios and their configurations through a literature survey, and discussions with local stakeholders and external experts. This stage results in two applicable scenarios for rural settings they would be installed in. At this point, those two stages are parallel to the Designing stage partially covered in the positioning of this research (Fig. 1). Finally, stage 3 entails validation of the two scenarios based on the extent to which each scenario meets the three sets of QAs. The data collection technique for this stage includes discussions with external experts, while the assessment protocol employs the Assessment Section of the Design Methodology for Appropriate Technology (DMAT) [86]. The result of this stage is the best



Note: (i) Indonesia; (ii) Sulawesi Island; (iii) North Sulawesi; (iv) Lake Tondano.

Fig. 3. Location of Lake Tondano in North Sulawesi, Indonesia, which is surrounded by 7 districts.

technological scenario that will serve as the selected technology for the pre-treatment process in the targeted rural context. Looking at the desired research activities, this research consists of five phases (Fig. 2). Phase 1 includes the Identification of Research Problem, the Building of Research Framework, and the Research Design. Phase 2, 3, and the beginning of Phase 4 practically relate to the three steps of the regulative cycle covered in this study. Then, the later part of Phase 4 ends the research by clarifying answers for the research questions of this study (**Q1**-**Q3**), including practical recommendations and theoretical insights from the results of this study.

3.2. Case study

This study takes an effort to develop biomass production technology from water hyacinths in the Lake Tondano area as the case study. The Lake Tondano (Fig. 3) is a natural water body and part of Tondano Drainage Basin, connecting no less than 35 inlet streams from rivers, agricultural irrigation as well as residential channels, and only 1 outlet stream to the Tondano River that empties into the Manado Bay [111]. The lake is surrounded by seven districts in North Sulawesi, Indonesia. It is the province's largest lake, covering an area as much as 4,278ha at about 600 m above sea level [111–113]. Ecologically speaking, it serves the surrounding ecosystem in different ways [112,114]. It is a critical source for germplasms that supply genetic materials to the environment. Besides, its water flow is currently utilised for two Hydroelectric Power Stations (HPS; *i.e.*, Tanggari and Tonsea Lama) that supply most parts of Minahasa Regency and Manado City. The water is also taken as a source of raw water for rural residential, industrial, and agricultural activities around the lake. In addition, the lake acts as the reservoir for excessive water from rainfall, surface flows, and underground flows. In fact, the lake's ecosystem is critical in maintaining the surrounding microclimate by influencing local humidity and precipitation levels. Economically speaking, the lake is a source of consumable fishes, which hence provides livelihoods for local fishermen. There are also several transportation modes utilising the lake to connect surrounding rural areas. Then, outsiders visit Lake Tondano as a tourism destination for its beautiful natural landscape. In short, disruption to the lake's condition would be expected to affect the economic, environmental, and social sustainability of numerous activities connected to the lake's ecosystem [111,114].

However, the lake is being flooded with water hyacinth, which is continuously changing by nature yet persistently covering certain areas. Literature have reported that water hyacinths could cover more than 850ha or no less than 20% of the lake's surface [113,115,116], with the highest incremental daily growth at 3% [117]. Considering the fundamental role of the lake towards its surrounding area [112,114], the water hyacinth problem has produced interrelated problems affecting organisms in the lake and rural communities living around it. For years, local people and regional governments have been trying to remove the water hyacinths from Lake Tondano by manually collecting them to open more spaces for the fish population to grow [118–120]. However, it requires high labour forces and investment with less returns, making them hesitant to continue the effort in a longer term. To overcome the water hyacinth problem more sustainably, local researchers have suggested converting water hyacinths into bioenergy (biomass) for electricity generation [117]. Stakeholders in the region, including the state-owned energy company (*Perusahaan Listrik Negara* – PLN), regional governments, and local communities, have indicated their interests. While establishing their plan, however, they cannot ensure sustainable use of biomass production technology. In other words, their concern is parallel with the interest of this study. There should be an analysis on the technological appropriateness of potential biomass production technology for the rural context of the Lake Tondano area, which would include alternative designs as the scenarios fitted with local conditions. Those situations thus make the water hyacinth problem in Lake Tondano a suitable case study for this research.

4. Proposed solutions

4.1. Field problem investigations

Typical rural areas consist of three stakeholders: the community, experts, and the government [121,122]. Table 1 provides the number of interviewees/discussants in each group of stakeholders. In this research, the community refers to inhabitants of the Lake Tondano area, who lack economic resources since the level of development is considerably low. In a brief observation, the inhabitants indicate a desire for better living conditions, ranging from better healthcare to improved farming yields. During interviews, the community, especially farmers in the Lake Tondano area, express their concerns about the shortages of fertiliser in the area. As the result, they cannot utilise their land to its highest potential, reducing food availability for the community. The concerns highlight the importance of community involvement in developing a sustainable solution for the Lake Tondano. Community members indicate that they would like to participate in realising a solution to the problem, which would contribute to increased living conditions. When asked about possible solutions, one can notice their limited technical knowledge. When presented with the option to utilise the water hyacinths as a source of energy and fertiliser, the community acts surprised about the possibility. Regardless, the community is semi-positive towards the solution, indicating that the final products (energy and fertilisers) are highly required in the Lake Tondano area. Furthermore, expert stakeholders are subdivided between local experts and external experts. Scholars from Sam Ratulangi University (Manado) and officials from the energy company (PLN) are the local experts since they are closely located from the Lake Tondano area. Scholars from Hasanuddin University and the Bandung Institute of Technology (*Institut Teknologi Bandung* – ITB) are the external experts alongside manufacturers of the given pre-treatment technologies included in scenarios. The two universities are located further away from the lake area, yet they can assist in measuring the perceived benefits in terms of LED (Hasanuddin University), and they possess valuable knowledge on the implementation and operation of the technologies (ITB). Besides, the experts act as a driving force in this LED effort. The community is highly dependent on the experts to train them to improve the current effort or introduce new programs in the future. In fact, the government relies on experts for the development of a detailed effort. The government refers to national, regional (province), and local (district and sub-districts) governments and related agencies involved in curbing water hyacinths in Lake Tondano. Table 2 shows the desired technological appropriateness in each tier of technological appropriateness, which are coded as Quality Attributes (QA).

4.2. Solution design

Considering the position of planned scenarios targeting specific process (pre-treatment) within BSC, several design decisions must be made [49,62]. In this study, the decisions are constrained by local factors, making a sharp contrast to typical biomass studies, which largely focus on pre-determined technical and economic considerations following an environmental concern. Thus, it is important to first specify the characteristics of the biomass source (water hyacinths) in the Lake Tondano. The biomass types can be categorised as (1) woody plants, (2)

Table 1
Interviews/discussions with stakeholders through purposive sampling.

Stakeholders	Research Phase			no. of interviewees/discussants
	2	3	4	
Community members	X	X	X	15
Local experts	X	X		5
External experts	X	X	X	11
Government officials	X	X	X	3

Table 2
Desired Quality Attributes (QAs) according to interviews.

Quality Attribute (QA)	ID	Description
Techno-economic Appropriateness		QA1
Low costs	**QA1.** A	Investment and operational costs should be as low as possible. Maximum investment is USD 800,000 when applying for the national governments' budget.
Scalable	**QA1.** B	The biomass pre-treatment technology should be appropriately scaled. For future expansion, it should be able to increase the processing/ conditioning capacity.
Understandability	**QA1.** C	Transfer of knowledge should be provided for the rural community. The technology should be simple and understandable, so the community will be able to operate and maintain the technology without requiring continuous external experts.
Robust	**QA1.** D	The biomass pre-treatment technology should be able to run continuously and withstand local conditions, such as the rainy season, droughts, and high temperatures.
Ease of implementation	**QA1.** E	The implementation should be easy to implement for the community. An external expert should provide technical guidance to ensure correct implementation.
Environmental Appropriateness		QA2
Utilise all water hyacinths	**QA2.** A	The biomass pre-treatment technology must help resolving the water hyacinth problem in the Lake Tondano in such a way that the water hyacinths are eliminated or sustainably utilised.
Low environmental impact	**QA2.** B	The biomass pre-treatment technology should have low environmental impacts, of which GHG emissions are the indicator to probe the impact.
No loss of natural habitats	**QA2.** C	To preserve biodiversity/natural habitats, the biomass pre-treatment technology should be realised within given locational constraints.
Environmental best practice	**QA2.** D	The biomass pre-treatment technology should serve as a best practice on how to utilise natural resources to other similar cases in Indonesia and beyond.
Social Appropriateness		QA3
Acceptance	**QA3.** A	The biomass pre-treatment technology will only perform properly if the stakeholders, of whom the community is the most important, acknowledge its necessity and utility.
Community involvement	**QA3.** B	One of the key drivers is to increase the economic development in the Lake Tondano area. The jobs that will be created by the biomass pre-treatment technology should be granted to the community.
Organisational standard	**QA3.** C	It should be ensured that mutual organisational norms are adopted, and priorities are in line between the different parties involved with the biomass pre-treatment technology.
Area's aesthetics	**QA3.** D	The construction/installation of the biomass pre-treatment technology should be carefully considered as such that it will not significantly decrease the aesthetics of the area.

herbaceous plants/grasses, (3) aquatic plants, and (4) manures [39]. In this study, the water hyacinths of Lake Tondano are the biomass type, which can be categorised as aquatic plants. Table 3 depicts the characteristics of the water hyacinths on the lake.

The second decision influences required pre-treatments, expected capital, operational costs, and expected environmental impacts [53,56,101]. Water hyacinths is wet biomass [39] since the plant has a moisture content of around 90% [36]. Technically speaking, having an extremely high moisture content has made the bio-chemical conversion technique of water hyacinths through anaerobic digestion (AD) most applicable [101,102,125,126]. AD turns organic material into so-called biogas directly, which is a mixture of mainly carbon dioxide and methane, and

Table 3
Characteristics of water hyacinths in Lake Tondano.

Characteristics	Water hyacinths
Biomass yield [t/ha/yr.][a]	120
Total biomass yield [t/yr.]	33,240
Moisture content (%)[b]	90
Availability of water hyacinths[b]	All year round
Purchasing price [USD/t_{wet}]	0

[a] The existing body of knowledge states biomass yields that differ between 29 [t/ha/yr.] [123] and 320 [t/ha/yr.] [124]. An expert acknowledged that the yield could differ that much and pointed out to use a yield of 120 [t/ha/yr]. in order to not overestimate the yield.
[b] Source: Abdelhamid & Gabr [36].
c Source: Akinwande et al. [123].

sludge [32,127–130]. Besides, AD is commercially proven, and water hyacinth is a good biomass source for the conversion technology [32]. Particularly, the sludge, which essentially is a by-product of the process, contains a high concentration of nutrients that improves the yields of different crops, making it a highly valuable organic fertiliser [50]. After searching for potential biomass production technology in Indonesia, two potential manufacturers are found to be specialised in AD technology, and they are willing to make their technologies able to process water hyacinths as the biomass source.

This study proposes the two distant scenarios to open possibilities for configuring design solutions for the water hyacinth problem in Lake Tondano. During discussions with external experts, a dedicated, one-station system emerges as the first scenario. Alternatively, AD lends itself for a small, modular system as the second scenario. Table 4 specifies relevant techno-economic data for both scenarios. Furthermore, both scenarios will be professionally run because the harvesting demand (pre-treatment capacity) can be met almost entirely by a mechanical harvesting machine or a couple of full-time workers. Besides, a professionally run pre-treatment stage allows the introduction of organisational standards [**QA**3.C] and requires less GHG-emitting transportation activities through villages surrounding Lake Tondano [**QA**2.B]. Then, demand contracts from the state-owned electricity company (PLN) that are agreed upon for a period of ten years are valid for both scenarios. For the first operational year, PLN will pay the pre-treatment stage USD 0.10 per kWh-equivalent biomass feedstocks, and the regional government USD 0.40 per kg and USD 1.60 per litre for solid and liquid organic fertiliser, respectively.

4.3. Solution validation: Scenario analysis

4.3.1. Scenario 1: High-tech

This scenario incorporates a dedicated, one-station system. It can process 30,000t water hyacinths per year, delivering a massively impacting solution for the problem [**QA**2.A] and can therefore count on

Table 4
Characteristics of designed scenarios.

Characteristics	*Scenario*	
	1: High-tech	2: Low-tech
Biomass capacity [t/yr.]	30,000	1,478
Output feedstock [kWh-equivalent/yr.][a]	5,256,000	74,095
Output solid fertiliser [t/yr.])[a]	300	887
Output liquid fertiliser [hl/yr.][a]	–	5,913
Automated	Yes	No
Service life [yr.]	20	10
Investment [USD]	2,321,867	145,849
Annual maintenance costs [USD/yr.]	48,034	3,196

[a] Both manufacturers pointed out that the actual output is dependent on the chemical composition of the water hyacinths. Since the composition is unknown due to seasonal variabilities and high analysis costs, the mentioned outputs are based on minimum values (pessimistic scenarios) defined by company experts.

acceptance from the community [**QA**3.A]. The manufacturer will construct the system and operate the start-up phase, while also providing necessary training to local workers on how to operate and maintain the technology. Moreover, the technology can be operated by an easy-to-use mobile application that allows for continuous monitoring and operations of the system. These aspects ensure that the technology is understandable [**QA**1.C] and easy to implement [**QA**1.E] for local workers. In the targeted BSC stage (pre-treatment), this scenario only requires a cleaning (conditioning) of the water hyacinths since the remaining activities are performed by the system. Because the scenario is implemented in a single location, it produces the lowest possible operational costs [**QA**1.A] at USD 17,260. Besides, the targeted stage would produce a low environmental impact [**QA**2.B] since there are only on-site manual logistics activities, and no loss of natural habitats is expected [**QA**2.C]. Besides, this scenario provides job opportunities for the operations, ensuring the involvement of local community in the pre-treatment process [**QA**3.B]. Then, required facilities will be constructed with less than 4 m height, preserving the aesthetics of the lake [**QA**3.D]. This scenario, therefore, provides techno-economic, social, and environmental benefits to the rural community, which will contribute to their acceptance [**QA**3.A].

Despite technical, environmental, and social benefits this scenario can offer, the economic analysis (Table 5) reveals its biggest disadvantage. The required investment for this scenario totals USD 2,527,866 or IDR 36.7 billion. The staggering amount tops available government budget more than three times, making it an overly expensive scenario [**QA**1.A]. The Discounted Payback Period (DPP) of this scenario equals 16.39 years, and the Internal Rate of Return (IRR) is −16.18%. Thus, this scenario is not feasible from an economic perspective. While this scenario requires a high amount of water hyacinths from the lake to sustain its use, the combination of high processing capacity beyond supply variability and low economic feasibility results in an undesirable potential for expansion [**QA**1.B]. Unfortunately, a solution to an environmental problem that creates no profitable business makes it a bad example for similar cases [**QA**2.D].

4.3.2. *Scenario 2: Low-tech*

In contrast to scenario 1, this scenario incorporates a small, modular system with an annual processing capacity of 1478 t/yr or about 5% of scenario 1 [**QA**2.A]. Due to the modularity, this scenario is easily expandable [**QA**1.B], overcoming acceptance hurdles that may arise. Besides, the utilisation is expected to reach 100% continuously since the capacity is way lower than the variability of water hyacinths supply. However, the system is semi-automated and requires more operational activities than scenario 1. The manufacturer will install the system and provide necessary training to local workers on how to operate and maintain the technology. This ensures that the technology is implemented properly [**QA**1.E] and is understandable [**QA**1.C]. In the targeted BSC stage (pre-treatment), this scenario requires cleaning (conditioning) and chopping (processing) of the water hyacinths. Because this scenario is small, it can be installed in proximity to the biomass source. Thus, it offers significant economic benefits to operational costs [**QA**1.A] with almost no GHG-emitting transportation required [**QA**2.B], and no natural habitats will be lost [**QA**2.C]. Due to the small-scale design, this scenario ensures the preservation of aesthetics of the Lake Tondano [**QA**3.D]. In short, the small-scale system of scenario 2 can show its techno-economic, environmental, and social benefits to rural stakeholders, therewith increasing their acceptance of the solution [**QA**3.A].

Due to more activities involved, this scenario allocates more job opportunities, ensuring the involvement of rural stakeholders in the pre-treatment process [**QA**3.B]. It will well diffuse the technology into the rural community, increasing social acceptance of the given technology. Perhaps, the biggest advantage of scenario 2 relates to the economic analysis (Table 6). Investment required to realise this scenario totals USD 212,491 or IDR 3.08 billion, falling well into the range of available budget of the government. With a positive cash flow of USD 1,253,915 in its first operational year, this scenario offers the possibility of a profitable pre-treatment process in the Lake Tondano area [**QA**1.A]. The first scenario has DPP at only 0.17 year (±2 months), while it has a staggering IRR value at 590.1%. Economically speaking, the Scenario 2 is highly feasible and can function as a good example [**QA**2.D] to similar cases by gradually resolving an environmental problem while providing impactful economic benefits in a rural context lacking economic resources.

4.3.3. *Comparative assessment*

To determine the technological appropriateness, the scenarios are assessed according to the QAs (Table 2). Table 7 provides an assessment matrix to compare and contrast the scores of both scenarios. In general, there are three observations for the first tier of technological appropriateness (techno-economic). First, the economic analysis of scenario 1 (Table 5) implies that the scenario is not economically feasible [**QA**1.A]. The required investment for scenario 1 is not possible to make from the subsidy budget of the government, resulting in a financial inadequacy of USD 1.7 million. Besides, the IRR of −16.18% makes it practically unattractive to external investors. In contrast to scenario 1, the required investment for scenario 2 falls within available budget of the government. There should, however, be noted that subsidy from the government is primarily applicable to energy production systems with high throughput. Since scenario 2 has a limited processing capacity, the government may reject a proposal as such. In contrast, the economic analysis of scenario 2 (Table 6) shows it as an extremely feasible option with an IRR of 590.07% and a DPP of only 0.17 year (±2 months), making it a highly attractive investment. Furthermore, the second observation focuses on the scalability of the technology [**QA**1.B]. Scenario 2 is easily expendable because additional module(s) can be easily installed at a little cost (USD 145,849). Besides, the expansion promises additional jobs for local communities. In contrast, expanding scenario 1 is less attractive due to the high investment costs (USD 2,321,867). Besides, the scenario has utilised much of the biomass supply, making any expansion to require more water hyacinths supply than available. If the expansion of scenario 1 is forced by considering the use of other biomass sources (*e.g.*, farmers' waste), additional collecting activities must be performed, increasing operational costs and probably GHG-emission by significant margins. It would increase investment even further since much more logistics activities are required to realise the additional biomass supply mechanism. Then, the final observation for the first tier of technological appropriateness focuses on production technology. In fact, the technology for scenario 1 is similar to that of

Table 5
Economic analysis of Scenario 1.

Characteristics	Scenario 1
Required investment [USD]	2,527,866
Annual income [USD]	645,600
Annual costs [USD]	356,943
Cash flow [USD]	288,657
Net present value after five years [USD][a]	−1,425,191

[a] Discount rate of 9.7% is based on suggested value by Griffin [131].

Table 6
Economic analysis of Scenario 2.

Characteristics	Scenario 2
Required investment [USD]	212,491
Annual income [USD]	1,308,270
Annual costs [USD]	54,355
Cash flow [USD]	1,253,915
Net present value after five years [USD][a]	4,577,488

[a] Discount rate of 9.7% is based on suggested value by Griffin [131].

Table 7
Technological appropriateness for Scenario 1 and 2.

	Quality Attributes (QA)	ID	Scores	
			Scenario 1	Scenario 2
1st tier	Low costs	**QA**1.A	–	++
	Scalable	**QA**1.B	–	++
	Understandable technology	**QA**1.C	++	+
	Robustness	**QA**1.D	+	+
	Ease of implementation	**QA**1.E	+	+
2nd tier	Utilise all water hyacinths	**QA**2.A	++	–
	Low environmental impact	**QA**2.B	+	++
	No loss of natural habitats	**QA**2.C	o	o
	Environmental best practice	**QA**2.D	–	+
3rd tier	Acceptance	**QA**3.A	+	++
	Community involvement	**QA**3.B	+	+
	Organisational standard	**QA**3.C	++	++
	Area's aesthetics	**QA**3.D	+	+

Note: - highly negative; - negative; o neutral; + positive; ++ highly positive.

scenario 2. However, the manufacturer involved in scenario 1 is able to integrate a mobile application that provides guidance to workers for operational and maintenance activities. This increases the technical understandability of scenario 1 over that of scenario 2 [**QA**1.C].

For the second tier of technological appropriateness (environmental), scenario 1 holds a major benefit over scenario 2. The processing capacity of scenario 1 is about 20+ times bigger than that of scenario 2 [**QA**2.A]. Due to the low utilisation of biomass sources by scenario 2, its environmental impact is lower than scenario 1. Regardless, scenario 1 enables a sustainable method to deal with the water hyacinths problem in Lake Tondano, which will contribute to regenerating Lake Tondano as a proper breathing ground for fish population. In conjunction with the expandability of scenario 2, however, the scenario provides a gradual resolution to the water hyacinths problem, since profits from the business can be reinvested to expand the pre-treatment technology, create more jobs, and increase the utilisation of water hyacinths in Lake Tondano. Thus, only scenario 2 could serve as a best practice [**QA**2.D] to similar cases. Scenario 2 shows how a profitable business can be realised while it simultaneously functions as a gradual solution to the water hyacinth problem. In terms of the third tier of technological appropriateness (social), scenario 2 holds one critical benefit over scenario 1 in terms of social acceptance [**QA**3.A]. It has become apparent that stakeholders, especially the community, hold more values leaning to the availability of organic fertiliser than that of energy. Considerably, organic fertiliser is, in contrast to energy, a visible product that is widely believed to increase farmer's yields and income. It can also strengthen food security in the entire North Sulawesi province. In general, scenario 1 is highly efficient in supplying biomass feedstock for energy conversion facility, while scenario 2 produces more fertilisers than the feedstock. These facts coupled with the social perspective influence the social acceptance of the rural community to favour scenario 2 over scenario 1. Then, those three tiers of technological appropriateness are scored to determine which scenario is most applicable for the Lake Tondano area. Based on the decision-making sub-stages of DMAT [86] with data from Table 7, Fig. 4 depicts these absolute scores per tier and per scenario. Although the scores are almost equal, scenario 2 visually performs better in the first and third tiers, whereas scenario 2 holds the second tier. Thus, scenario 2 is stated as having the higher technological appropriateness among the two proposed scenarios, meaning that scenario 2 is the most applicable to the Lake Tondano area. In general, it offers the possibility of a profitable business with relatively low investment costs, scalable technology, and social benefits to the area.

5. Discussion

Basically, it is difficult to control the growth of water hyacinth due to its rapid regeneration, which happens mainly from fragments of stems [22,28,132,133]. The current cleaning activities undertaken by the government and PLN have led to nothing but merely a temporary removal of water hyacinths. Choosing scenario 2 as the more appropriate solution due to its technological appropriateness, which includes techno-economic, environmental, and social tiers, requires further considerations on the amount of water hyacinths it can process. As a single installation, scenario 2 has a capacity of 1478 t/yr, for which a surface area of 12ha covered with water hyacinths will suffice. In its non-expanded state (early application), scenario 2 will not be a sustainable solution to the water hyacinth problem. A sustainable solution is defined in this study as the method(s) applied to utilise the water hyacinths in a resource-efficient manner, therewith restoring the fish population in the lake to its previous levels, providing economic advantages, and delivering social benefits to the community. Thus, choosing scenario 2 *will* require a follow-up on its expansion to increase the processing capacity. The expansion can make us of the accumulation of small revenue fractions from an existing installation(s) to scale up the number of installations. Over time, the expansion(s) will deliver more revenues for further expansions until the capacity can cope up with the

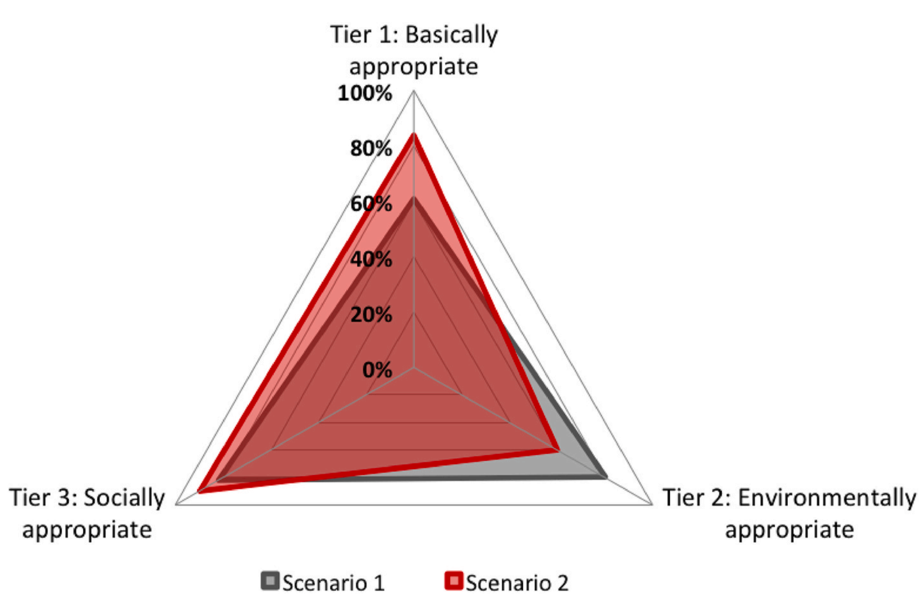


Fig. 4. Simple comparison of technological appropriateness between scenarios.

growth of water hyacinths. The maximum scale shall maintain the full utilisation of the technologies (without unused capacity) to ensure sustainable revenues. At that point, the maximum expansion will deliver optimum environmental impacts with the highest possible economic benefits, understandable technicalities, and maintained social acceptance for a longer time horizon. During the process of expansion, other side uses of water hyacinths (*e.g.*, feed livestock, for handicraft production, organic compost, *etc*.) are advised to cope with the growing speed of remaining water hyacinths [28,32,36,134]. While the expansion gradually increases revenues from the biomass pre-treatment process, the community can benefit from the side uses of harvested water hyacinths. However, other possibilities may arise, threatening the sustainability of the extended scenario. This study shows that utilising water hyacinths for biomass pre-treatment process offers the possibility of a profitable business. Once the first facility is installed, the community, but more importantly people with close ties to investors, will see its true economic values. Possibilities will arise that those other parties want to build the same pre-treatment facility as well. This can result in a proliferation of parties who want to utilise water hyacinths, which threatens the long-term sustainability of the originally proposed solution. To prevent this from happening, experts point out the importance of involving local governments in regulating the harvesting of water hyacinth in Lake Tondano. The governments may, for instance, issue utilisation permits to interested parties. On the other hand, the scenarios are assessed according to desired QAs by stakeholders in three tiers of technological appropriateness. From a techno-economic perspective [57,88], the selected scenario is simply feasible to be implemented in the Lake Tondano area. For the second tier (environmental appropriateness) [47,58], however, there is acute unavailability of data on environmental impacts [63], implying the needs of more research to quantify all emissions emitted by assessed scenario(s) to air, water, and land [135]. When designing the whole BSC in a rural context, those emissions may then be further incorporated to identify the impacts of certain scenario (s) to climate change, human health, and the quality of rural ecosystem.

Regarding the third tier (social), it is even more difficult to quantitatively probe all intangible social aspects [46,60]. Thus, workarounds are needed to ensure social benefits to rural stakeholders without having to pursue quantifications for all social indicators. As an example, community participation in the making of control policy regarding water hyacinths and in the development of a sustainable solution for the environmental problem could overcome possible conflicts [136]. The second social challenge concerns a possible interference with food [137] or other goods and material supply chains [138]. Water hyacinths will not pose a direct threat since the plant will not be eaten, yet stakeholders shall pay attention to a total solution that does not interfere but improve fish farming activities in the Lake Tondano. The third challenge involves exposure to health risks while working with any biomass pre-treatment process [139]. Water hyacinths have been known to affect the health conditions of people working with the plant or living in its proximity [32]. Water hyacinth mats floating around a lake serve as a breeding ground for vector organisms that carry Schistosomiasis (*Bilharziasis*), malaria, and river blindness [36]. Despite expecting negative health effects in the Lake Tondano area due to the presence of water hyacinths, the issue requires dedicated studies. The case of Lake Tondano, however, requires a dedicated study in the near future to understand and mitigate the health risks before starting any operations. Furthermore, another typical challenge for the sustainability of biomass development is the adoption of mutual organisational norms, rules, and standards [140]. In a rural context, those norms, rules, and standards considerably fit if the biomass production technology(ies) is installed or concentrated on one location. It simplifies how community runs the business, making it relatively easy to adopt mutual organisational norms, rules, and standards. Finally, perhaps the most important social challenge is to ensure community involvement and stakeholders' acceptance [63,86,121]. To generate the acceptance, the project shall first convince local leaders and critical stakeholders on the necessity and advantage of planned biomass production technology. Those leaders and critical stakeholders are the gatekeepers [86,141] of the newly targeted location, who would open the gate to introduce the desired biomass production technology to the location. It would be easier if there is an existing biomass production technology operating in another location. Techno-economic, environmental, and social impacts of the showcase would be critical to deliver convincing messages to the leaders. In practice, the information shall prefer quantitative data to show that the biomass production technology is feasible, after which the showcase shall provide an overview of how a total solution to the water hyacinth problem is highly possible to realise. After convincing the gatekeepers, the next stage is to convince the community and other stakeholders in a similar manner. The presence of the convinced gatekeepers will make it easier for the rest of rural stakeholders to believe the information being presented since they deeply respect their leaders.

6. Conclusion and implications

To curb the excessive growth of water hyacinths in rural areas, physical, biological, and chemical cleaning programs hold little value-added, hence attracting less interest from rural stakeholders, and making the cleaning remain unsuccessful. In general, the typical programs introduce high investment and operational costs, and merely result in temporary removals of water hyacinths. This study proposes biomass production technology to utilise the water hyacinths in rural areas as a source of biomass for bioenergy production and the provision of organic fertiliser. Considerably, this would pose a more sustainable solution, by which the utilisation of water hyacinths could provide socioeconomic benefits to the community while addressing an environmental problem. Regardless, this research argues that, for such technologies to be feasible, the introduction process must consider the technological appropriateness of the biomass production technology. By taking a design science approach, this study incorporates the argument to answer the research questions. This study argues that rural context has its particularities lacking techno-economic resources and limited knowledge. Proposing a biomass production technology, therefore, must ensure the technological appropriateness of the (given) technology to the rural context it will be installed in. To deliver a thorough decision-making, a parallel assessment of potential scenarios (alternative biomass production technologies) shall produce comprehensive judgements over the choice of technology with the highest possible technological appropriateness in the rural settings among the alternatives. Scenarios for the assessment must be the results of discussions with potential providers of biomass production technologies, considering their technical capabilities and willingness to adapt with particularities of targeted rural areas. The characteristics of each scenario may vary according to available technologies from the providers. Technically, the assessment would include qualitaty attributes (QA) as the set of desired techno-economic, environmental, and social characteristics of biomass production technology according to rural stakeholders. Rural stakeholders are the community, experts (local and external), and the government. Discussions with the stakeholders will form a comprehensive set of QAs from different points of view solely for the improvement of circumstances if a (selected) technology is eventually applied. The QAs must centre on the idea of how a biomass production technology being assessed will interact with existing circumstances in the target location. Gathered QAs depict the potential interactions in three tiers of technological appropriateness (techno-economic, environmental, and social). The assessment is practically a miss-and-match of the techno-economic, environmental, and social performances of an assessed technology to the desired QAs. In the end, the assessment would result in a selected technology that can fulfil the greatest number of QAs, indicating the highest technological appropriateness among proposed biomass production technologies.

The results of this study provide various implications for academics, policymakers, and practitioners. First, this study contributes to the body of knowledge of biomass production technology for rural context from three perspectives of technological appropriateness (techno-economic, environmental, and social). Practitioners working on similar cases can use the results as an example of feasible option in addressing environmental concerns with proper technical performances while also promoting socioeconomic developments for rural communities living around the location of the environmental problem(s). For locations with an enormous potential of biomass resources, this study shows that local communities can get multiple techno-economic, environmental, and social benefits from utilising the biomass sources. Therefore, policy-makers can learn from both the results and challenges rising in this study to ensure proper regulations that can maintain the sustainability of biomass production and its techno-economic, environmental, and social impacts. For both academics and practitioners, the process of assessing technological appropriateness introduced in this study can serve as a blueprint to contribute to the transfer of design knowledge from experts to rural communities. The transfer of knowledge is a critical value for their own biomass production efforts by empowering rural communities to utilise biomass as a viable source of bioenergy and organic fertiliser instead of seeing it as a source of waste that holds no socioeconomic value.

Author statement

Lantos A. Pin: Writing - Original Draft, Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data Curation, Visualization, Project administration. **Bartjan J.W. Pennink:** Conceptualization, Methodology, Formal analysis, Resources, Writing - Review & Editing, Supervision, Project administration. **Herman Balsters:** Conceptualization, Resources, Writing - Review & Editing, Supervision. **Corinthias P.M. Sianipar:** Conceptualization, Methodology, Validation, Formal analysis, Writing - Review & Editing, Visualization, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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