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Assessing community perceptions on the socio-economic feasibility of green mussel cultivation in Demak, Indonesia

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ABSTRACT

Coastal communities in Demak, Indonesia, face increasing socio-environmental challenges due to land subsidence, sea level rise, and economic vulnerability. This study assesses the socio-economic feasibility of green mussel (*Perna viridis*) cultivation on bamboo structures as a Nature-based Solution (NbS) for coastal protection and livelihood improvement. A structured survey was conducted among 337 respondents across 13 villages, focusing on demographic distribution, financial and market feasibility and key barriers. Using Latent Class Cluster Analysis, three distinct clusters were identified. Cluster 1 had balanced demographics and moderate interest in green mussel farming, with concerns over capital and poaching. Cluster 2 showed strong investment interest, easy market access, and highlighted poaching and licensing as key issues. Cluster 3 had the oldest, least educated group, low investment interest, and mentioned lack of capital and skills as key barriers. The study found that proximity to infrastructure and aquaculture exposure influence investment interest in green mussel farming. Younger, educated individuals and aquaculture workers showed more willingness to invest. These insights highlight the importance of tailoring NbS interventions to local socio-economic and geographic contexts. Targeted microcredit schemes, capacity building, community-based monitoring and participatory design processes are necessary to enhance the socio-economic feasibility of green mussel farming on bamboo structures.

1. Introduction

1.1. Problem definition

Demak is a regency on the north coast of Central Java, Indonesia. In the 15th century, Demak was a significant port city during the Sultanate era, controlling much of Java's northern coast [1]. Demak has a population of approximately 1.2 million inhabitants and covers 995 km^2, comprising 14 districts and 249 villages (Fig. 1a). Despite its rich history, Demak increasingly faces environmental challenges which can be linked to the regency's economic decline in combination with climate change and demographic growth.

Demak's coastal zone is part of a low-lying plain shaped by both riverine and marine processes. Several rivers and channels drain into the Java Sea along this coast, delivering freshwater and sediment that contribute to a predominantly muddy coastline [2]. This coastline is characterised by silty intertidal flats and was historically fringed by mangrove forests, which provided natural coastal protection and habitat for local biota. Oceanographically, the region experiences a microtidal regime (tidal range on the order of ~0.5 m) and is largely sheltered from ocean swell, meaning waves are primarily driven by local winds [3]. Seasonal monsoonal currents further influence coastal dynamics by dispersing river plumes alongshore, which affects sediment distribution and water conditions [4]. These environmental features set the stage for Demak's coastal challenges.

Coastal villages in the districts like Sayung, Karang Tengah, and Bonang (Fig. 1a) face multiple challenges such as land subsidence, sea level rise, erosion, and coastal flooding. Land in Demak subsides with 80–180 mm per year [5–8], while the sea level rises by 5.52 mm per year [7]. Villages such as Bedono and Timbulsloko (Fig. 1b) have already lost a significant portion of their land in the last decade.

Sea level rise, driven by increasing greenhouse gas emissions and consequent climate change, is a global phenomenon, whereas land subsidence is a regional issue along Java's north coast. The causes of

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subsidence in Java and Demak are complex and multifaceted. Alluvium soil characteristics contribute to subsidence, yet anthropogenic factors, notably industrial groundwater extraction, worsen the problem [9,10]. Groundwater extraction is prevalent due to inadequate surface water alternatives, illegal practices, insufficient water security investments, and ineffective governance [6]. Furthermore, land use changes, such as aquaculture and infrastructure expansion, have led to mangrove loss, intensifying coastal erosion and subsidence impacts [9,10].

Land subsidence, the root cause of the coastal flooding, causes severe damage to local communities in Demak, including cracks in buildings, road and bridge damage, house tilting and destruction, and the loss of fishponds [11]. Sriwulan village, for instance, experiences daily flooding ranging from centimetres to over a metre, losing 60 hectares of land between 2003 and 2016, including fishponds and settlement areas [12]. Another example is Sayung village, with a coastal retreat of 79.2 km between 2015–2022, resulting in 12.14 hectares being permanently flooded [2].

Demak's economy heavily depends on coastal and terrestrial ecosystems. Until the 1980s, the economy relied on dry-land crops (e.g., spices, corn, coconut) and rice. Since the 1980s, it has gradually shifted to aquaculture due to rising domestic and global demand for shrimp (*P. Indicus, P. Monodon*) and milkfish (*chanos*) [13]. Despite these changes, 15.72 % of the population still lives below the poverty line of USD 29.05 per capita per month [14,15].

Over the past decade, efforts to mitigate coastal erosion and flooding in Demak have included studying and, in some cases, implementing various adaptation measures. These measures fall into three main categories: conventional hard infrastructure, Nature-based Solutions (NbS), and hybrid engineering. Conventional hard infrastructure, such as the proposed seawall in Demak, aims to protect coastal areas using man-made structures [16]. NbS, such as mangrove rehabilitation and bamboo structures, utilise natural ecosystems to combat climate change and coastal challenges, benefiting humans and biodiversity [3,17]. Hybrid engineering integrates NbS with hard infrastructure, combining features like seawalls with natural solutions to maximise coastal protection [18,19].

Embedding adaptation measures in a policy context is essential to manage the effects of climate change and coastal flooding effectively. Effective adaptation policy enhances resilience and preparedness by identifying gaps in laws and regulations, guiding governance processes, securing funding, and developing frameworks to measure progress [20–22]. Indonesia has ratified key international agreements such as the United Nations Framework Convention on Climate Change (UNFCCC, Law No. 6/1994), the Kyoto Protocol (Law No. 17/2004), and the Paris Agreement (Law No. 16/2016) [23]. These laws emphasise climate change mitigation, adaptation, and disaster risk reduction, aiming to protect vulnerable areas, recognise national commitments, and secure access to funding and technology.

Several high-level adaptation policies incorporate these laws. The National Action Plan for Climate Change Adaptation (RAN-API) provides a comprehensive legal framework for climate change adaptation strategies [24]. The Enhanced Nationally Determined Contribution (NDC), submitted to the UNFCCC in 2021, aims to improve resilience in economic, social, and ecological domains [25]. The Climate Resilience Development Policy outlines long-term strategies for low-carbon development and climate resilience from 2020 to 2045, promoting sustainable development and adaptive capacities across sectors [26]. Additionally, the National Roadmap on Mitigation and Adaptation to Land Subsidence, developed in 2019, focuses on coastal and water management, climate action, and sustainable ecosystem management, including empowering local communities [27]. These policies are translated into numerous other laws addressing disaster management,

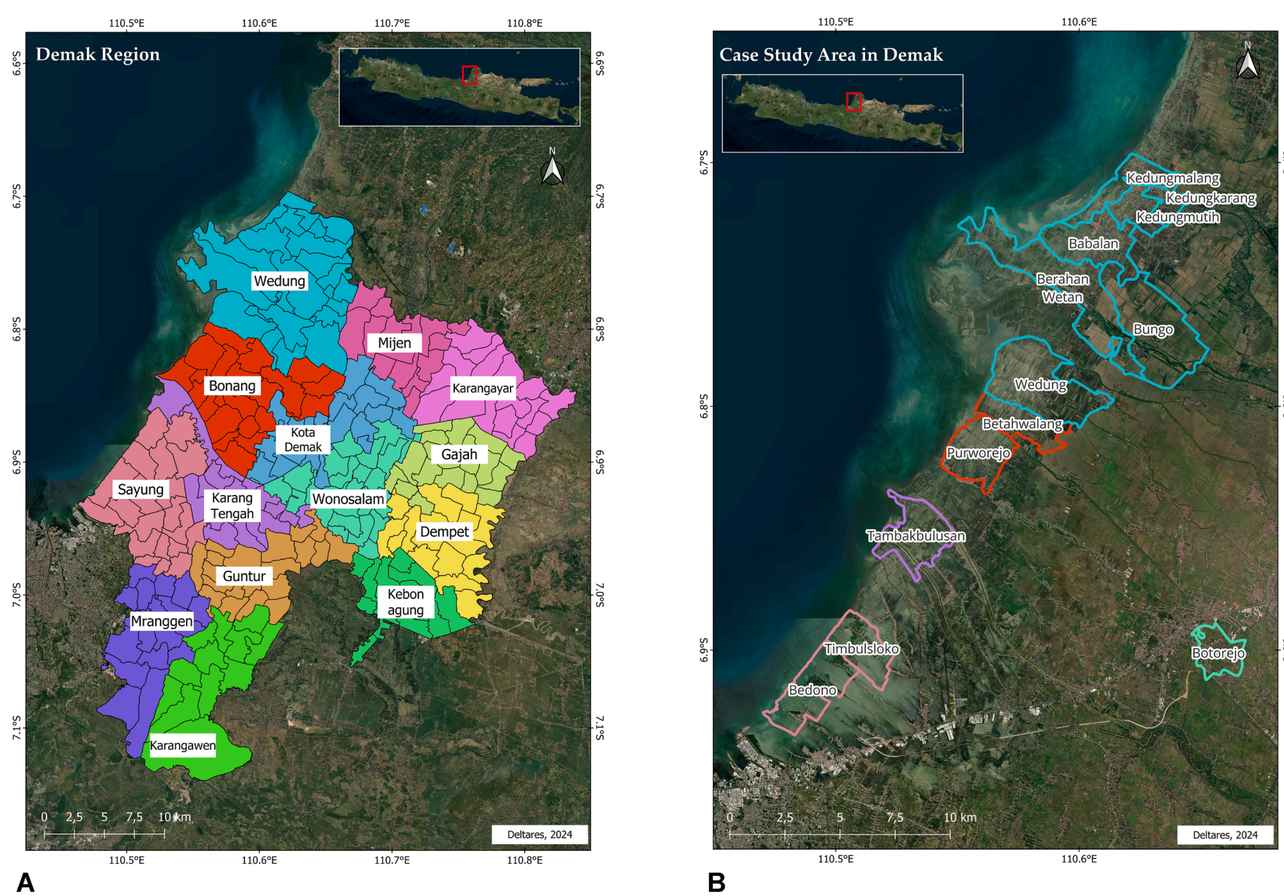

Fig. 1. (a) Map of Demak Regency with its districts and village boundaries (b) Selected villages for the survey (made by authors).

housing in flood-prone areas, water resource management, coastal area protection, meteorological data collection, geospatial information, marine affairs, and local government roles [23].

Conventional hard infrastructure measures to address coastal erosion and flooding have proven ineffective and costly in addressing the challenges of Demak's soft and muddy coastline [28]. In response, several NbS projects were initiated. From 2015 to 2021, Building with Nature Indonesia restored mangrove habitats and enhanced aquaculture productivity, fostering social cohesion among coastal communities [29]. Building on these results, the MuMaCo project (2021–2026) aims to develop a strategy specifically tailored to the restoration of Demak's muddy coasts. One of the assignments within the MuMaCo project is to explore the feasibility of using dual-purpose vertical bamboo piles for stabilising the coast while integrating mussel culture, aiming to revitalise both the environment and local economies (Fig. 2) [30].

Green mussel (*Perna viridis*) cultivation using longline systems has been shown to outperform traditional bamboo stake methods in terms of spat collection, growth rates, and economic returns. In Demak, longline culture yielded nearly twice the income per unit of labour compared to stake culture, while also offering a mangrove-friendly alternative that avoids land conversion and supports sustainable livelihoods in erosion-prone coastal zones [31]. Despite these promising results, green mussel farming remains a relatively new practice in Demak, with only several dozen farmers currently engaged in the activity. Yet, it is currently unknown how coastal communities perceive the socio-economic feasibility of green mussel cultivation on bamboo structures.

1.2. Objective

The objective of this paper is to assess the socio-economic feasibility of green mussel cultivation on bamboo structures in Demak, Indonesia, based on community perceptions and an indicator-based assessment. The community-based perceptions of socio-economic feasibility entail the following categories: demographic distribution, market & financial feasibility and key barriers. The Demak Regency in Java, Indonesia, serves as the case study area.

1.3. Reading guide

The paper is structured as follows. Chapter 2 presents the theoretical framework, providing the theoretical background and context. Building on this, Chapter 3 details the methodology, outlining the research design and procedures employed. Chapter 4 examines the results obtained from the study. Finally, Chapter 5 offers a discussion, summarising the results, interpreting the findings and comparing them within the broader scientific context.

2. Theoretical background

2.1. Nature-based solutions

Nature-based Solutions (NbS), in the context of coastal management, refer to management strategies to improve flood protection as well as other societal benefits by making use of natural materials and dynamics throughout the life cycle of the intervention [32,33]. Examples of Coastal NbS may include sand nourishments such as the Sand Engine, where currents, waves and tides distribute the sand along the shoreline. NbS may also include the restoration of oyster or mussel reefs acting as wave breakers, contributing to water purification. Another example includes the restoration of mangrove forests, trapping mud and reducing wave intensity, or permeable sedimentation dams in muddy environments [3,34–36].

Using vertical bamboo piles to stabilise the coast, combined with mussel culture, fits in this line of thinking [37]. Bamboo structures in muddy environments have the potential to contribute to flood protection by reducing wave energy, trapping mud and reducing erosion [3,4,37]. If planning occurs in a participatory or engaging way, it can also contribute to awareness of coastal processes and the benefits of NbS. Moreover, combining the sheltered conditions with mussel farming has the potential to contribute to food production, job security and income in a coastal zone.

2.2. Assessing the socio-economic feasibility of nbs

While NbS measures are usually first assessed on their biophysical effects and feasibility, understanding socio-economic effects and feasibility is as relevant to successfully implementing an intervention. As a systematic approach to assess interventions, socio-economic feasibility assessments provide insight into expected socio-economic effects, risks, and into the degree the intervention is considered possible and/or desirable [38,39]. The assessments also highlight desired or required technical, governance or institutional changes [40,41]. Hence, a socio-economic feasibility assessment can be used to support decision-making.

Socio-economic feasibility assessments are a specific form of indicator-based assessment, which is a widely used methodology in environmental management. Next to gaining insight into the impact of and support for an intervention, such an assessment enables comparison of interventions, tracking status over time of an area or comparing different areas [42–44].

Indicators provide the basis against which the thought-up intervention is assessed [45]. An indicator is “a component or a measure of environmentally relevant phenomena used to depict or evaluate environmental conditions or changes or to set environmental goals” [46]. With the help of indicators, the number of parameters and measurements required to make an assessment can be reduced and communication simplified [47]. Although it is important to use the best available knowledge in selecting indicators and setting suitable targets, indicator selection and simplification are not always a strict scientific process but can also result from negotiations and expert judgment [47,48]. Hence, the selection of indicators can be biased and linked to assumptions deriving from world views of those included in the selection process [49].

While aligning the bottom-up selection of indicators with international standards, as encouraged by James [45], three categories of indicators to assess the socio-economic feasibility of NbS can be identified, including demographic distribution, market and financial feasibility and key barriers (Fig. 3).

Demographic indicators are essential for understanding the human context in which NbS are implemented. According to FAO [50], variables such as age distribution, education levels, and occupation provide insights into the socio-economic characteristics of coastal communities. Demographic indicators help assess the community’s capacity to participate in and benefit from NbS interventions. For example, a younger population with limited livelihood options may be more inclined to engage in NbS-based aquaculture activities. Incorporating demographic data into socio-feasibility assessments ensures that interventions are tailored to local needs [51].

Market and financial indicators assess whether the NbS intervention can be economically viable and self-sustaining. This includes, for example, willingness to invest, market access, and consumption patterns [52,53]. Scientific literature highlights that economic viability is a key determinant of long-term success, especially in low-income coastal areas where alternative livelihoods are limited. Without a clear market pathway, even ecologically sound interventions may fail to gain traction or be scaled up. As Le Coent et al. [54] emphasise, economic assessments are essential to determine the feasibility of NbS for decision-makers and investors.

Identifying key barriers for local communities to engage in NbS is essential for the successful implementation of NbS interventions. In the context of NbS-based aquaculture, key barriers might include, for example, a lack of knowledge and a lack of access to capital [52].

Fig. 2. Bamboo structures for green mussel aquaculture in Demak. Photo credits: Ristiawan Nugroho.

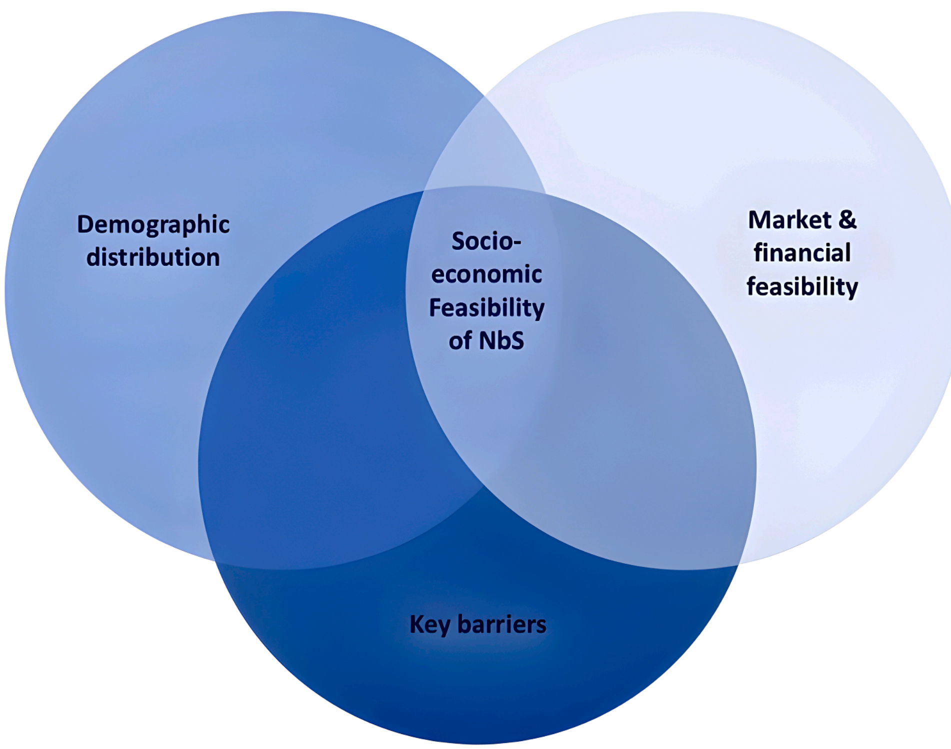

Fig. 3. Three categories to assess the socio-economic feasibility of NbS (made by authors).

Literature on NbS stresses that such barriers often determine the gap between theoretical feasibility and practical implementation [41]. For instance, even if the ecological and economic conditions are favourable, weak governance can negatively impact the project. Therefore, a barrier analysis is important to identify and mitigate risks and tailor the intervention to the needs of the local communities.

3. Methodology

3.1. Setting up the survey

The methodology for developing the structured survey followed five main steps, as shown in Fig. 4. The first step involved reviewing theoretical frameworks to identify relevant indicators. The frameworks used included the Ecosystem Services theory [55–57], the Doughnut Economy theory [53], and the multi-criteria model by Barbosa Junior et al. [58], which helped identify barriers to the adoption of sustainable

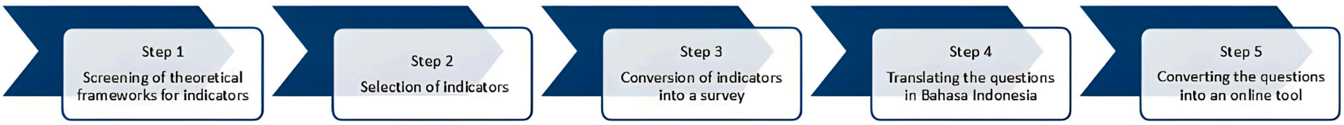

Fig. 4. Overview of steps for setting up the survey (made by authors).

agriculture.

In the second step, 42 relevant indicators were selected from the chosen frameworks. These indicators were grouped into three main categories: demographic distribution, financial and market feasibility, and key barriers. Utilising expert judgement, each indicator was assessed for its relevance to NbS and its suitability to the specific context of Demak Regency. Subsequently, the indicators were translated into survey questions to support data collection.

The third step focused on adapting the questions to suit the target population, including fishers, pond farmers, shellfish collectors and fish traders. Their backgrounds and education levels were considered to ensure the language was appropriate and easy to understand. The draft survey was then reviewed by independent senior experts in socio-economics, stakeholder engagement, and tropical aquaculture.

The fourth step involved translating the final draft of the survey into Bahasa Indonesia to ensure accessibility for local respondents. In the fifth and final step, the survey was converted into an online format. It was tested to confirm that it functioned correctly, was suitable for the target audience, and could be accessed from Indonesia.[1]

3.2. Data collection

Data was collected between June and August 2024 across 13 villages in Demak (Fig. 1b). Respondents from the fishery and aquaculture communities in these villages were recruited through the Extension Services of the Marine and Fisheries Institute. The surveys were administered via face-to-face interviews by experts and students of Diponegoro University, ensuring a personal and thorough data collection process. Following the completion of the fieldwork, the data gathered from the paper surveys were transferred into the online survey tool.

3.3. Sampling

According to the National Statistics Agency of Indonesia, out of 948,897 workers aged 15 and above in Demak Regency, 19.41 % are employed in the agriculture sector, which includes fisheries and aquaculture [14]. This proportion corresponds to approximately 184,200 individuals. Based on this population size, a sample of 337 respondents is generally considered adequate for producing reliable estimates, yielding a margin of error of approximately ±5.5 % at a 95 % confidence level.

The sample consisted predominantly of men (85.2 %), with women making up a smaller proportion (14.8 %). The gender imbalance was signalled early in the data collection phase. The interviewees were asked to increase their efforts to engage with female respondents during the interviews. This moderately improved the gender balance. The gender imbalance may be explained by the fact that only 15 % of women are employed in the agricultural sector, while the majority (around 54 %) are working in the services sector, including tourism and small businesses such as food stalls and shops [14]. In addition to sectoral employment patterns, social and cultural factors also play a significant role in shaping women's participation in agriculture. Traditional gender norms in rural Asia often assign women to domestic roles, limiting their involvement in formal agricultural activities [59]. Furthermore, women frequently face restricted access to land, credit, and agricultural training, which hinders their ability to participate equally in farming and aquaculture [60]. These structural and cultural barriers contribute to the underrepresentation of women in the agricultural workforce.

Most of the respondents were aged between 35–44 (26 %) and 45–54 (25 %). The 18–24 age group was underrepresented, comprising 6 % of the respondents. This may be explained by the fact that the younger generation prefers factory work over fisheries and agriculture. Most respondents attended elementary school as the highest form of education (53 %), while 19 % completed secondary school and another 19 % finished high school. Additionally, 6 % of the respondents had not received any education. Key occupations among the respondents include fishers (49.6 %), while 19.9 % are pond farmers and another 12.8 % are shellfish collectors. A small group of respondents consisted of pond workers and (shell)fish traders.

3.4. Data analysis

The quantitative analysis consisted of a Latent Class Cluster Analysis (LCCA - [61]). LCCA is a statistical method used to uncover hidden subgroups - latent classes or clusters - within a population by analysing multiple variables, whether categorical or continuous. As a type of finite mixture modelling, LCCA assumes the population comprises distinct, unobserved classes or clusters. Each of these latent classes has a unique profile of responses or measurements. The principle behind LCCA is that the population's overall distribution is a blend of several distinct distributions, each representing a different latent class. This method recognises the population as heterogeneous, composed of multiple subgroups with unique characteristics. A significant feature of LCCA is probabilistic assignment. Unlike traditional clustering methods that assign each individual to a single cluster, LCCA calculates the probability of an individual belonging to each latent class. Typically, individuals are assigned to the class for which they have the highest probability, acknowledging the uncertainty in the assignment process and offering a more nuanced data interpretation [61].

The LCCA was performed on the survey dataset of 337 responses, using Latent GOLD Basic 6.0 software. This analysis grouped respondents into distinct clusters based on variables from three categories of indicators: demographic distribution, financial & market feasibility, and key barriers. In practice, the LCCA incorporated demographic data (e.g. respondents' age group, education level, primary occupation, and area of residence) to capture the community's socio-economic background. It also included financial & market indicators derived from the questionnaire (e.g. the willingness to invest in green mussel cultivation, perceived ease of selling mussels and obtaining a fair price in local markets, the popularity of mussel consumption in their village, and the main community benefit they associated with mussel cultivation). In addition, the LCCA used barrier indicators to account for obstacles perceived by the community; these included factors like lack of access to credit or loans, insufficient knowledge and skills, risk of poaching (theft of mussels), lower expected income, and other challenges identified in the survey. The purpose of the data analysis was to gather a comprehensive picture of local perceptions and conditions related to green mussel cultivation, so that the LCCA could identify latent clusters of

[1] Consult the supplementary materials for the final set of indicators and survey questions.

[2] Consult the supplementary materials for a description of the methodology to select the appropriate statistical model and the results of the selected model.

respondents with similar profiles. These clusters, in turn, reveal patterns in how different segments of the community perceive the socio-economic feasibility of cultivating green mussels on bamboo structures. In summary, the analysis leveraged specific survey inputs from the Excel database to statistically determine sub-groups of respondents. This approach provides a nuanced understanding of which factors most strongly influence local support or hesitation regarding green mussel cultivation.

4. Results

Based on the LLCA, three main clusters were identified, representing 48 %, 29 %, and 23 % of the respondents[2] (Table 1). The demographic distribution includes areas of residence, education, age, and occupation. Financial and market indicators encompass willingness to invest, market access, perceptions regarding price, popularity of consumption, and community contributions. Finally, key barriers to the implementation of mussel cultivation on bamboo structures are discussed.

4.1. Demographic distribution

Cluster 1 comprised inhabitants from Bedono, Bungo, and Timbulsloko in the southern and northwestern areas of Demak. This cluster had an evenly distributed age range between 25 and 54 years. Education levels were relatively balanced among elementary, high school, and secondary school, with the majority having an elementary school education. The primary occupations in this cluster were fishers, followed by cockle/green mussel collectors and fish/shellfish traders. Notably, this was the only cluster that included green mussel farmers, accounting for 7 % of the respondents.

Cluster 2 mainly included inhabitants from Bedono, followed by Babalan and Wedung. Compared to cluster 1, this cluster had a higher concentration of respondents in the 18 to 25 age range and those over 52 years old. The education level in cluster 2 was lower, with more than half of the respondents having an elementary school education and 12 % having completed secondary school. The dominant occupations were fishers and pond farmers, making this cluster the largest group of pond farmers. There were no green mussel farmers or respondents with other occupations within this cluster.

Cluster 3 included more than half of the inhabitants from the villages of Berahan Wetan, Bungo, and Betahwalang in the northern area of Demak. This cluster had a relatively older population (44 % were older than 54), with fewer respondents in the 18 to 34 age range. Cluster 3 had the lowest education levels, with the majority having an elementary school education and no respondents having completed high school. A total of 17 % did not receive any formal education, the highest among the three clusters. The primary occupations in this cluster were cockle and green mussel collectors, fishers and fish/shellfish traders. The professions in this cluster were relatively evenly distributed.

Villages like Bedono and Bungo appear in multiple clusters due to the diverse demographic and occupational profiles of the respondents. LCCA identifies patterns at the individual level rather than grouping entire villages, allowing the same village to belong to different clusters.

Table 1
Demographic dimensions of the LLCA. See supplementary materials for the full dataset.

Size		Cluster 1 48 %	Cluster 2 29 %	Cluster 3 23 %
Main village of residence		Bedono (25 %)	Bedono (64 %)	Berahan Wetan (19 %)
		Bungo (17 %)	Babalan (11 %)	Bungo (19 %)
		Timbulsloko (16 %)	Wedung (8 %)	Betahwalang (14 %)
Age distribution	<18	0 %	0 %	1 %
	Age 18–24	4 %	10 %	5 %
	Age 25–34	29 %	15 %	7 %
	Age 35–44	29 %	31 %	16 %
	Age 45–54	26 %	22 %	27 %
	>54	12 %	22 %	44 %
Education	University	1 %	0 %	3 %
	High school	25 %	22 %	0 %
	Secondary school	30 %	12 %	6 %
	Elementary school	41 %	59 %	73 %
	No formal education	1 %	6 %	17 %
	Unknown	1 %	0 %	1 %
Main occupation	Cockle/green mussel collector	12 %	1 %	29 %
	Fish/shellfish trader	10 %	1 %	22 %
	Fisher	56 %	52 %	33 %
	Freelancer	2 %	0 %	4 %
	Green mussel farmer	7 %	0 %	0 %
	Pond farmer	8 %	46 %	11 %
	Other job	4 %	0 %	1 %

4.2. Financial & market feasibility

Cluster 1 comprised a majority of respondents who expressed a willingness to invest in green mussel cultivation in the villages of Bedono and Timbulsloko, which represented a large part of this cluster (Table 2). An exception was Bungo, which showed a lower willingness to invest, ranging from 25 % to 50 %. Most respondents in cluster 1 perceived market access as moderately accessible. However, obtaining a fair price for selling the product on markets was considered more challenging, with responses ranging from neutral to not easy. Most respondents in cluster 1 considered green mussel consumption to be extremely to somewhat popular. The main community contributions of cultivating mussels on bamboo structures were jobs and income, with

Table 2
LLCA of financial & market feasibility. Some answers are not included due to their small proportions and readability of the table. See supplementary materials for the full dataset.

	Answer category	Cluster 1	Cluster 2	Cluster 3
Willingness to invest in green mussels	Yes	73 %	100 %	27 %
	No	27 %	0 %	70 %
Market access	Extremely easy	42 %	59 %	18 %
	Somewhat easy	26 %	17 %	39 %
	Neutral	14 %	22 %	23 %
	Not easy	13 %	2 %	12 %
	Extremely not easy	1 %	0 %	1 %
Fair price	Extremely easy	8 %	32 %	3 %
	Somewhat easy	18 %	21 %	19 %
	Neutral	38 %	39 %	43 %
	Not easy	32 %	5 %	26 %
	Extremely not easy	2 %	1 %	3 %
	I do not know	2 %	0 %	4 %
Popularity of consumption	Extremely popular	39 %	65 %	13 %
	Somewhat popular	31 %	27 %	26 %
	Neutral	20 %	1 %	31 %
	Not popular	9 %	5 %	21 %
	I do not know	1 %	0 %	8 %
Community contribution	More income	53 %	69 %	73 %
	More jobs	33 %	12 %	24 %
	Less flooding	2 %	8 %	0 %
	Higher social status	2 %	0 %	0 %
	Increased food and nutrition security	6 %	6 %	1 %
	Increasing biodiversity	1 %	4 %	0 %
	Community development	3 %	0 %	1 %

other contributions considered less important.

Cluster 2 showed a unanimous willingness to invest in green mussel cultivation for the villages of Bedono, Babalan, and Wedung. A majority of respondents in this cluster perceived market access for selling green mussels as very easy, coinciding with the high popularity of green mussel consumption. Obtaining a fair price was considered extremely easy to easy by more than half of the respondents. In cluster 2, respondents indicated the highest popularity of green mussel consumption compared to the other clusters. Similar to cluster 1, income was considered the main community contribution, followed by job creation, with a combined response of 81 %. Other contributions included reduced flooding and increased food and nutrition security.

Cluster 3 showed the lowest willingness to invest in green mussel cultivation. The majority still considered market access to be somewhat easy to neutral, with only a few respondents indicating it was extremely difficult. Cluster 3 mainly comprised villages in the mid-northern area of Demak, which generally showed a lower willingness to invest in green mussel cultivation, except for Wedung and Babalan. Market accessibility and obtaining a fair market price for green mussels were considered the least favourable in cluster 3 compared to the other clusters. The popularity of green mussel consumption was also the lowest in cluster 3, with responses evenly distributed among somewhat popular, neutral, and not popular. The main community contributions identified were income and jobs, with a combined 97 % of the responses, the highest among the three clusters.

4.3. Key barriers

Overall, the key barriers reported were lack of access to loans, lack of knowledge and skills, and risk of poaching (Table 3). In all clusters, respondents were less concerned about access to inputs such as bamboo, lack of time, changes in tradition, and lack of social networks.

Cluster 1 respondents identified the lack of access to loans or privately owned capital as the primary barrier, followed by the risk of poaching and the lack of knowledge and skills. Among the three clusters, cluster 1 had the highest concern about access to inputs such as bamboo, though this was still relatively low at 9 %. Lack of time and changes in rituals and traditions were negligible across all clusters.

Cluster 2 respondents considered the risk of poaching as the foremost barrier, followed by a lack of access to loans or capital. Poaching was a more prominent barrier in Wedung, Kedungmutih, and Kedungmalang. Additionally, the barrier of "lower expected income" was highest in cluster 2 compared to the other clusters. Notably, cluster 2 was the only cluster that identified the lack of a license to operate as a barrier.

Cluster 3 respondents perceived the lack of access to loans or privately owned capital and the lack of knowledge as the key barriers, followed by lower expected income. In contrast to the other clusters, poaching and lack of access to inputs were not considered significant barriers. This also applied to a lack of time, social network inputs, or licenses, where the percentages were very low.

Table 3
Key barriers identified in LLCA, some answers not included due to their small proportions and readability of the table. See supplementary materials for the full dataset.

	Answer category	Cluster 1	Cluster 2	Cluster 3
Key barrier	Lack of access to loans or privately owned capital	46 %	24 %	55 %
	Lack of knowledge & skills	14 %	20 %	24 %
	Lower expected income	8 %	12 %	10 %
	Risk of poaching	16 %	30 %	4 %
	Change of traditions or rituals	3 %	0 %	1 %
	Lack of access to inputs (Bamboo, Seed, etc.)	9 %	4 %	4 %
	Lack of Social Network	1 %	2 %	0 %
	Lack of Time	2 %	1 %	0 %
	No License to Operate	0 %	6 %	1 %

5. Discussion

The objective of this paper was to assess the socio-economic feasibility of green mussel cultivation on bamboo structures in Demak, Indonesia, based on community perceptions and an indicator-based assessment. This chapter summarises the key findings, discusses the interpretation of the results and the theoretical and policy implications of the findings. The chapter finishes with a section on the methodological considerations.

5.1. Summary of results

The demographic distribution focused on age, education, and occupation. Respondents in cluster 1, covering Bedono, Bungo, and Timbulsloko, had a balanced age range and education levels, with most working as fishers and a small group farming green mussels. Respondents in cluster 2, mainly from Bedono, had a younger and older population mix, lower education levels, and consisted mostly of fishers and pond farmers, with no green mussel farming. Respondents in cluster 3, from Berahan Wetan, Bungo, and Betahwalang, had the oldest population and the lowest education levels, with a more even spread of occupations, including fishers and shellfish collectors.

The financial and market feasibility of green mussel cultivation was assessed by focusing on willingness to invest, perceptions of market access and fair pricing, and the perceived benefits to their communities. Respondents in cluster 1 showed moderate willingness to invest in green mussel cultivation, particularly in Bedono and Timbulsloko. Market access was seen as moderately easy, but fair pricing was a concern. Mussel consumption was generally popular, and the main benefits cited were income and job creation. Respondents in cluster 2 showed unanimous investment interest, with easy market access and high consumption popularity. Income and jobs were the key contributions, alongside benefits like reduced flooding. Respondents in cluster 3 had the lowest investment interest and the least favourable views on market access and pricing. Mussel consumption was less popular, though income and jobs remained the primary perceived benefits.

The key barriers identified across all clusters were limited access to capital, lack of knowledge and skills, and the risk of poaching. Other issues, such as access to inputs, time constraints, changes in tradition, and weak social networks, were less significant. Respondents in cluster 1 perceived a lack of capital as the biggest challenge, followed by poaching and limited skills. Concerns about inputs like bamboo were slightly higher here, but still minor. Respondents in cluster 2 ranked poaching as the top barrier, followed by a lack of capital and skills. This cluster also reported the highest concern about a lower expected income and uniquely mentioned licensing issues. Respondents in cluster 3 focused on the lack of capital and skills, with lower expected income as a third concern. Poaching and input access were not seen as major issues.

5.2. Interpretation of results

The results suggest that proximity to infrastructure and exposure to existing aquaculture initiatives may influence demographic and occupational diversity. The older, less educated respondents in cluster 3 may reflect limited mobility and access to information, with the risk of reinforcing socio-economic marginalisation.

The willingness to invest in green mussel cultivation was highest in cluster 2, particularly in Babalan and Wedung. This may be attributed to perceived market opportunities and the popularity of mussel consumption in these areas. Education and age appear to play a role: younger and more educated individuals (clusters 1 and 2) showed greater investment interest, possibly due to higher risk tolerance and better access to information. Occupation also influenced attitudes – pond farmers and fishers, for instance, were more inclined to invest, likely due to familiarity with aquaculture practices.

Perceptions of market access and fair pricing varied across the clusters. Cluster 2 respondents reported the most favourable market conditions, aligning with the high popularity of mussel consumption. This suggests a positive feedback loop, where consumption is high, market feasibility is perceived as stronger, reinforcing investment interest. In contrast, a negative feedback loop is suggested in cluster 3, with lower levels of consumption and the least favourable market conditions, which could discourage investment.

Barriers differed significantly across clusters. Lack of capital was the most cited barrier overall, particularly in cluster 3, highlighting the need for financial support mechanisms. Poaching emerged as a key concern in cluster 2, especially in Wedung, suggesting localised security issues that could undermine the success of cultivating mussels on bamboo structures. Knowledge gaps were also dominant, particularly in clusters 1 and 3, indicating a need for targeted training and capacity building.

5.3. Theoretical and policy implications

This study contributes to the growing body of literature on NbS by demonstrating the value of combining generic and context-specific indicators. While barriers such as capital and knowledge are commonly cited in NbS literature, poaching emerged as a location-specific barrier, underscoring the importance of tailoring NbS assessments to local realities [51]. The findings support the argument that socio-economic feasibility is not merely a function of economic indicators but also of indicators relating to social dynamics and perceived risks.

Recent literature underlines that socio-economic feasibility is shaped not only by technical and socio-economic factors but also by broader socio-political conditions [62,63]. In the context of NbS, effective governance structures, equitable power dynamics, and cultural legitimacy may be other relevant factors for feasibility assessments. For example, strong participatory governance can enhance the legitimacy of green mussel cultivation, while unresolved power imbalances or unfair benefit-sharing may limit community buy-in [64,65]. This paper touched on several of these socio-political conditions, such as highlighting social status gains and community development benefits (Table 2) and the role of local traditions and rituals (Table 3). However, aspects like power relations and equity considerations were outside the scope. As these factors may also play a role in assessing the socio-economic feasibility of green mussel cultivation, it is recommended that these factors are included in future research. Including these aspects would enable a more holistic feasibility assessment – aligning with recent insights on the role of inclusive governance and social equity in successful NbS [62,63].

To enhance the feasibility of green mussel cultivation on bamboo structures in Demak, several short-term and longer-term policy interventions are recommended. It is recommended to address these interventions simultaneously. I.e. access to capital is useless if a farmer is not aware of appropriate aquaculture techniques and business skills.

- Microcredit schemes (short-term intervention): Address the widespread lack of capital, particularly in cluster 3. These should be tailored to local investment capacities, which were not fully captured in the LCCA but could be explored in follow-up studies.
- Poaching prevention strategies (short-term intervention): Implement community-based monitoring or cooperative models in villages like Wedung.
- Education and training (longer-term intervention): Focus on improving aquaculture techniques and business skills, especially in villages with low education levels and high knowledge gaps.

These interventions should be geographically differentiated, reflecting the distinct profiles and needs of each cluster.

The findings of this study offer practical guidance for scaling NbS. Participatory design processes are essential to ensure local ownership and reduce barriers. For instance, involving communities in the design of bamboo structures could mitigate poaching and enhance acceptance. Targeting younger, more educated individuals in villages with a high green mussel consumption may accelerate adoption and create demonstration effects for neighbouring communities.

While these strategies offer a promising pathway for scaling NbS through community engagement and targeted outreach, recent findings highlight emerging challenges that must also be addressed to ensure long-term success. Green mussels and other filter-feeding molluscs are known to accumulate pollutants when present in their environment, including heavy metals bound to fine sediments [66,67]. Over the past years, studies have reported this along the north coast of Java [68–71]. These studies stem from a period prior to the mangrove greenbelt in MuMaCo's study area [72], which could help shelter suspension-feeding molluscs from exposure to certain contaminants.

To safeguard public health, it is essential to evaluate the need for depuration as part of the planning and implementation of future aquaculture initiatives, in line with global best practices [73]. Public education on safe consumption limits, alongside robust regulatory frameworks to ensure compliance, will be critical to the success of green mussel farming. Additionally, spatial data on pollutant distribution should inform site selection to ensure that farming locations meet established safety standards.

5.4. Methodological considerations

The use of LCCA enabled the identification of hidden socio-economic patterns in the data, offering a nuanced understanding of community segmentation. The sample exhibited a gender and age imbalance, with women and youth underrepresented. This limits the generalisability of findings, particularly regarding household-level decision-making and intergenerational perspectives.

The results largely validated the selected indicators, confirming the relevance of both global (e.g., capital, knowledge) and local (e.g., poaching) dimensions. The framework's flexibility allowed for the integration of diverse socio-economic realities. However, refinement is needed. For instance, poaching should be considered a standard indicator in similar contexts, and indicators should be co-developed with communities to ensure cultural and contextual fit. Future studies should test the methodology in other NbS contexts to assess its transferability. Co-creation of indicators with local stakeholders is recommended to enhance relevance and legitimacy.

Supplementary materials

- The overview of indicators and survey questions: https://doi.org/10.5281/zenodo.15607455
- The method to select the appropriate LCCA model, including results: https://doi.org/10.5281/zenodo.15607201
- The full dataset: https://doi.org/10.5281/zenodo.15606283

CRediT authorship contribution statement

Bas Bolman: Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Rizka Akmalia:** Writing – original draft, Investigation, Data curation, Conceptualization. **Isten Tamba:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Wesley van Veggel:** Writing – original draft, Methodology, Formal analysis. **Heleen Vreugdenhil:** Writing – original draft, Methodology, Conceptualization. **Restiana W. Ariyati:** Validation, Methodology, Investigation, Data curation. **Lestari L. Widowati:** Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Ristiawan Agung Nugroho:** Formal analysis, Data curation. **Sri Rejeki:** Validation, Supervision, Methodology, Data curation.

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 paper.

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Data availability

We provided to the link to the data in the document

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