

Environmental, economic and social assessments of waste management strategies for Bonaire

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The research aims to understand the social, economic and environmental impact of various waste management strategies proposed to deal with organic waste in Bonaire (including the management of Sargassum). The research included field work in Bonaire focusing on the impact of Sargassum beaching's and the second stage was to conduct a multi-criteria analysis (MCA) to assess four different waste management strategies. These strategies included various methods such as composting, anaerobic digestion and the use of black soldier fly larvae (BSFL). Based on the MCA, Strategy 2, which uses BSFL, performs slightly better than Strategy 1 (composting) and Strategy 3 (clean anaerobic digestion) in terms of social and economic impacts, whilst Strategy 3 performs the best environmentally. However, the differences are small, and overall, Strategies 1-3 perform well across all criteria, particularly when compared to the baseline landfilling strategy and Strategy 4 (omnivorous anaerobic digestion).

Key words: Bonaire, sargassum, multi-criteria analysis, organic waste management, socio-economic impacts, environmental impacts

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List of Abbreviations

AHP	Analytical Hierarchy Process
BONHATA	Bonaire Hotel and Tourism Association
BSFL	Black Solder Fly Larvae
CAT	Circularity Analysis Tool
CBS	Central Bureau voor de Statistiek (Statistics Netherlands)
GHG	Greenhouse Gas
ILT	Inspectie Leefomgeving en Transport
MAUT	Multi-Attribute Utility Theory
MCA	Multi-Criteria Analysis
OLB	Openbaar Lichaam Bonaire
STMP	Strategic Tourism Masterplan
TEA	Techno-Economic Assessment
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
WCR	Wider Caribbean Region

1 Introduction

1.1 The BonCirc project

In the project 'Sustainable and Circular Organic Waste and Sargassum Management on Bonaire' (short name: BonCirc), circular approaches to the sustainable management of organic waste streams on Bonaire are developed.¹ On Bonaire, organic waste is collected jointly with other waste and mostly landfilled. This causes greenhouse gas (GHG) emissions, nutrient leakage and eutrophication of natural environments and the coastal habitat. Since 2018, Bonaire has experienced Sargassum beachings that negatively affect the ecosystem (Figure 1), causing environmental damage to coastal ecosystems when not harvested near the shore. The raise in Sargassum events in the Caribbean Sea has been partly attributed to several factors, including nutrient enrichment, increased temperature and other changes in climate (Robledo et al., 2021). This Sargassum biomass is currently landfilled after collection. Considering other societal challenges experienced on the island, including food security and economic development, the idea to use Sargassum biomass in a meaningful way has gained foothold.



Figure 1 Sargassum beaching at Lagun seashore in May 2025
Source: WFBR.

Within the BonCirc project, organic residues and wastes (food waste, agricultural residues, manure, garden waste, Sargassum, etc.) are mapped and assessed in terms of amounts over the year, composition, current uses and potential uses, circularity of current uses and expected development over time. Research was further carried out to valorise Sargassum biomass, that currently is disposed of, with the other organic wastes thereby creating (more) circular value chains that could contribute to regenerating natural (marine) habitats and agriculture.

¹ <https://www.wur.nl/en/project/circular-uses-of-organic-biomass-streams-in-bonaire.htm>

1.2 Objective and research questions

The objective of this study is twofold. First, it aims to assess the socioeconomic impact of the Sargassum beachings. Second, and building upon this assessment and other work done in BonCirc, it aims to comparatively assess the various waste management strategies developed against social, economic and environmental criteria. This assessment complements the other activities in the BonCirc project and, together, these aim to inform private and public sector about the potential to improve waste management practices on Bonaire.

There are therefore two main research questions:

- (1) What are the current socioeconomic impacts of the Sargassum beachings?
- (2) how do the various strategies for the co-processing of Sargassum and other organic waste on Bonaire compare, taking into account social, economic and environmental parameters?

Chapter 2 continues with a description of environmental and socioeconomic challenges on Bonaire, relevant in light of organic waste management. The report then has a description of the methodology used (Chapter 3), following by an analysis of the socioeconomic impacts of the Sargassum beachings (Chapter 4). For a description of environmental impacts, we refer to other BonCirc deliverables (van der Geest et al., 2024; Mûcher et al., 2024). Chapter 5 describes the different proposed strategies (which are combinations of innovations) for dealing with Sargassum and other organic waste management in Bonaire. The four different waste management strategies are Strategy 1: Composting & incineration; Strategy 2: Insects, composting & incineration; Strategy 3: Anaerobic digestion, composting & incineration; and Strategy 4: Omnivorous anaerobic digestion & composting. These strategies are assessed using Multi-Criteria Analysis in Chapter 6, with further discussion of main findings presented in Chapter 7.

2 Bonaire faces various environmental and socioeconomic challenges

Bonaire is the second largest Caribbean island within the Kingdom of the Netherlands, with a surface area of 288 km². It is situated around 90 km North of Venezuela and 40 km East of Curaçao. As of 2010, it is considered a Special Municipality or Public Body along with St. Eustatius and Saba within the Kingdom of the Netherlands, meaning it is governed by both an island authority and by the Dutch Central Government. Bonaire is governed by the Bonaire Public Entity (Openbaar Lichaam Bonaire - OLB). According to Statistics Netherlands (CBS),² the most recent recorded population in Bonaire is 24,090 (in the year 2023). The population number is steadily increasing due to an ongoing increase in development. The primary draw of Bonaire resides in its diverse nature, both marine and land-based, with popular activities particularly including water, such as windsurfing and diving. Among the most pressing issues on Bonaire are food security, climate change, waste management and economic development (including the reliance on imports to the island). The following section outlines in more detail the main environmental and socioeconomic challenges that are experienced in Bonaire, and the current waste management situation that is dominant on the island (landfilling).

2.1 Food security is under pressure with high prices and little local production

Bonaire imports the vast majority of its food, making it highly vulnerable to global supply chain disruptions, fluctuating prices, and external economic pressures. The limited availability of arable land and freshwater resources restricts large-scale agriculture (Post and Hengsdijk, 2023), leading to reliance on imported goods for staple foods such as rice, vegetables, dairy, and meat. This dependence on external markets exposes the island to food insecurity, particularly during global crises such as the COVID-19 pandemic, when shipping delays and price hikes affected food availability. Efforts to promote local food production face multiple obstacles, including poor soil quality, a dry climate with irregular rainfall, and a shortage of skilled agricultural workers. Although there are small-scale farms, including the LVV farm, and hydroponic³ initiatives, they struggle to meet the growing demand for fresh produce. Additionally, livestock farming is constrained by water scarcity and high feed costs, limiting the availability of locally produced meat and dairy products. Due to transportation costs, import taxes, and a lack of local competition, food prices in Bonaire are significantly higher than in the mainland Netherlands or on other Caribbean islands. This economic barrier disproportionately affects low-income households, leading to disparities in access to nutritious food and presents a major risk to food security (van der Geest and Slijkerman, 2019). High costs also discourage restaurants and hotels from sourcing locally, further reinforcing the reliance on imports.

2.2 Bonaire is vulnerable to climate change and energy costs

As a low-lying island, Bonaire is highly vulnerable to rising sea levels. Coastal erosion threatens key infrastructure, including roads, homes, and tourist facilities. The loss of beachfront areas also impacts marine biodiversity, particularly coral reefs that serve as critical ecosystems and natural barriers against storm surges. Bonaire's coral reefs are among its most valuable natural assets, attracting divers from around the world. However, rising sea temperatures, ocean acidification, and pollution are contributing to coral bleaching and reef degradation. This not only threatens marine biodiversity but also impacts tourism and the fishing industry (Schep et al., 2022; Oosterhout et al., 2023).

² Statistics Netherlands | CBS

³ <https://www.bonairedailyfresh.com/>

Bonaire, together with the Dutch government, is working on its own climate plan. This was initiated in 2023 with the Advisory report on the Climate Table Bonaire *It is never too late*. In this advisory report, the Quatermaker formulated ambitions for Bonaire's climate plan, concluding that:

- The Paris Agreement and the European-law obligations resulting from it only apply to the European part of the Netherlands. There are consequently no statutory obligations upon the Caribbean Netherlands to reduce emissions.
- Bonaire's mitigation ambition is to contribute to combating climate change. The ambitions for the Caribbean Netherlands have not yet been formalised.
- Bonaire has an adaptation task: in addition to its mitigation ambition, climate adaptation is very important for Bonaire.

Further detailing of the climate plan through the 'Climate Table' was started in February 2025.⁴

Bonaire depends heavily on imported fossil fuels for the provision of energy. Currently, 69% of the energy supply originates from the combustion of fossil fuels, equivalent to about 300 barrels of heavy oil per day. The remaining energy is generated from wind turbines (32%) and solar panels (1%). As a consequence, electricity costs are high and prices are vulnerable to fluctuations depending on oil supply. While environmental conditions on Bonaire offer opportunities for the generation of sustainable wind and solar energy, they require improvements to the electricity network. The global aspiration of reducing greenhouse gas emissions, as agreed upon by all members of the United Nations in the 2015 Paris Agreement, presents a potential opportunity for Bonaire to fund investment in renewables. The Netherlands has set its goal for a greenhouse gas emission reduction of 49% in 2030 compared to 1990. In 2050 the energy supply is to be fully sustainable.

2.3 Economic development lack diversity as it is highly dependent on tourism

Tourism is a major contributor to Bonaire's income, accounting for around 40% of the island's total income, with about 358 thousand cruise passengers⁵ annually on a population of 24 thousand (Verweij et al., 2020) (Figure 2). Direct tourism expenditure is estimated at around 40% of the Gross Domestic Product of USD 428m in 2017. Both direct and indirect tourist expenditure provide jobs for many residents, with jobs distributed across accommodation and food services (16%), recreation and cultural activities (9%), construction (7%), and wholesale and retail (14%).



Figure 2 Cruise ship in Bonaire

Source: P. Kuiper.

⁴ <https://open.overheid.nl/documenten/ronl-893aab0ab82170edcac62b164d4a745ab3dbad4e/pdf>

⁵ <https://opendata.cbs.nl/statline/#/CBS/en/dataset/85007ENG/table?ts=1742558186374>

This dependency on tourism makes the island's economy vulnerable to market fluctuations, global health issues and extreme weather events, such as the COVID-19 crisis, which completely shut down all tourism-related activities.

In the document *Economische ontwikkeling en diversificatie Saba, Sint Eustatius en Bonaire* (2023), the OLB has described the current situation and future priorities in relation to economic development and diversification. It describes how Bonaire has focused in past years on restoring the tourism sector post COVID-19. In addition, there is a Strategic Tourism Masterplan (STMP) with the aim of strengthening tourism to make the sector more resilient and to achieve responsible, balanced growth while preserving nature, culture and identity. The OLB further focuses on diversification of the economy by stimulating a number of other sectors, such as agriculture and technological and creative industries.

Verweij et al. (2020) conclude that Bonaire would benefit from having a more diversified economy, in which a diversity of sectors contributes more evenly to the economy and spreads the risk of slumps in one particular sector. A possible direction of economic development includes stimulating the further development of financial and IT services (requiring stable and high-speed internet facilities), biopharmaceutical industries, increased local vegetable and fruit production, and goat meat and brine shrimp (live food for fish) production. Such bio-pharmaceuticals and agricultural products have the potential to enhance exports both within the Caribbean region and through trade and transit ports, for example, between Europe and Latin America.

2.4 Priority actions for governance are developing a just society and adapting integral approaches

The *Bestuursakkoord Bonaire en Rijk 2024-2027* sets out the priority actions in governance on the island that need attention. It describes the long-term objectives and how the joint efforts of the State of the Netherlands and the Openbaar Lichaam Bonaire can contribute to achieving these. In the draft *Bestuursakkoord 2024-2027*, three priority areas are given:

1. Just Society (Rechtvaardige samenleving) in which residents can lead a dignified life, in which people care for each other and where the government offers a basic level of support, care and facilities that guarantees security of existence for everyone. A just society is also an inclusive society. This means reducing and preventing socioeconomic division and social exclusion by creating opportunities for participation and further development of the most vulnerable citizens.
2. Integral approach to Sustainable Development aimed at being able to better manage the development of the island, sustainably and focused on the needs of society. This administrative agreement gives priority to the realisation of public transport, improving the licensing, supervision and enforcement system (VTH), improving the infrastructure, and integrated area development.
3. A strong and participatory democracy (Krachtige en participatieve democratie) on Bonaire has a government apparatus that complies with the principles of transparency and good governance. This includes clarity about responsibilities and roles. It also includes clarity about the tasks of the organisation, where they are assigned and the reporting on achieved results. This requires an administrative organisation that is in order, a clear Planning & Control cycle and adequate internal and external communication.

2.5 Nature protection is needed to protect the wealth of biological diversity

Verweij et al. (2020, 2022) conclude that Bonaire hosts a wealth of biological diversity. Many species are endemic to the island, found nowhere else in the world. Its coral reef diversity and offshore diving attract many tourists. Apart from the marine diversity, the island itself offers diverse habitats that serve as a haven for dozens of animal and plant species, many of which are globally threatened. They also conclude that nature on Bonaire is vulnerable due to its small area and inherently small populations of species, making them particularly vulnerable to habitat loss, fragmentation and degradation.

In 2020 The Ministries of Agriculture, Nature and Food Security, Infrastructure and Water Management, and Interior and Kingdom Relations formulated the policy plan for nature and environment in the Caribbean Netherland, identifying the following four strategic goals:

1. Reverse coral reef degradation to enhance wellbeing in the Caribbean Netherlands
2. Restore and conserve the unique habitats and species in the Caribbean Netherlands
3. Sustainable use of land and water for the development of the local economy
4. Create the local conditions to ensure sustainable results of nature policy in the Caribbean Netherlands.

2.6 Waste management on the Bonaire is under pressure

In Bonaire the waste management is carried out by Selibon. There are developments in separate collection of different types of wastes (Figure 3) and in sending to recycle some of the streams. However, the majority of the wastes are landfilled. The largest landfill in Bonaire is the landfill of Selibon, which is situated within the Lagun district, and most waste streams largely end up in the landfill, including Sargassum, organic waste and other waste streams. The landfill creates several negative environmental and social impacts, particularly for residents of the Lagun district, who must contend with vermin, strong smells, and the illegal or accidental burning of waste. Burning of the landfill reduces air quality and can cover large areas of the island in toxic smoke. Water used to eradicate these fires leads to leaching of substances in the landfill such as heavy metals, which has led to the contamination of seawater in the bay of Lagun. This highlights potential risks to the environment and public health. The Inspectie Leefomgeving en Transport (ILT) (translated to Living Environment and Transport Inspectorate) has carried out inspections on the landfill and, in their inspection report *Permitting, supervision and enforcement at Selibon Lagun*, noted that the situation at the waste centre and the landfill in Bonaire is concerning, and there are complex challenges that need to be urgently solved.⁶

In addition to the landfill, there are nine unrefrigerated shipping containers on the site which contain biomedical waste that cannot be incinerated due to the closure of the incineration plant. These containers are in poor condition and also need to be dealt with. There are also 19 containers containing asbestos material.



Figure 3 Waste collection site of SELIBON

Source: WFBR.

⁶ [Situatie Selibon zorgwekkend, complex en urgent | Nieuwsbericht | Inspectie Leefomgeving en Transport \(ILT\): Inspection report: situation Selibon worrying, complex and urgent | News item | Rijksdienst Caribisch Nederland](#)

3 Methodology

A mix of research methods has been used to analyse the environmental, social and economic impact of various waste management strategies for organic waste in Bonaire. Chapter 4 presents the results of a qualitative study carried out in 2023, focusing on the socioeconomic impact of Sargassum beachings. The study included a series of site visits to landfills and interviews with various stakeholders in Bonaire from those in the tourism industry and local community, to those working directly in Sargassum management. The site visits helped the researcher to get a first-hand impression of the situation and were needed for the sorting and analysis of waste (Soethoudt et al., 2024).

To evaluate the social, environmental and economic impact of different organic waste management strategies, consisting of a combination of different innovation, a Multi-Criteria Assessment (MCA) methodology was used. The four organic waste management strategies that were evaluated in this research were developed as part of the BonCirc project by Lanting et al. (forthcoming), and a brief description is presented in this report. For a more detailed description of the strategies and their development, see Lanting et al., forthcoming.

3.1 Field Work Study

In 2023 fieldwork was conducted in Bonaire by Christle Nieuw—an MSC student at Wageningen University—under the supervision of Bas van Vliet (Environmental Policy Group, WUR) and Sander van den Burg (Wageningen Social & Economic Research). The full report (Nieuw, 2023) can be made available on request. The aim of the fieldwork was to gather insights into the social-economic impacts of the Sargassum beachings. The fieldwork was pre-empted by a brief literature review. This literature review offers insight into the socioeconomic impacts faced by these destinations due to frequent Sargassum influxes and the management approaches adopted in response.

A further examination of the socioeconomic impacts of frequent Sargassum influxes and the management approach in Bonaire was conducted through face-to-face, semi-structured interviews with organisations operating in sectors potentially affected, focusing on nature, tourism, and the local community. The questions formulated for the interviews underwent several reviews and tests from other researchers involved in other aspects of the research project, and a researcher based in Bonaire before being used. The questionnaire that was used during these interviews can be found in Appendix 1.

Interviewees representing different sectors were chosen based on their proximity to areas in Bonaire frequently impacted by Sargassum influxes. Additionally, other main actors in Sargassum management were identified through the STINAPA Marine Park Management Plan. Given that the entire cycle of Sargassum management spans from its arrival in the water to its disposal, the waste management organisation was also included in the interviews. Potential participants were contacted either virtually or in person and were offered a detailed consent form containing an introduction to the research, confidentiality agreements, and requested signatures to consent to the interview as well as separately to record said interview for data analysis purposes.

The interviews were semi-structured to allow flexibility, enabling deviation from the pre-designed questions to explore emerging insights during the interview. Moreover, the interviews were conducted in the respondent's preferred language, whether Papiamentu, English, or a combination of both. Eleven interviews were conducted in total, with nine allowing recording. The questions were aimed at participants both as sector representatives and as individuals personally affected within the local community. The overview of respondents can be found in Table 1. Interviews were carried out by the MSC student throughout the course of two weeks in May 2023.

Table 1 Overview of respondents

Respondents	Sector Representative
Respondent 1	Tourism and local community
Respondent 2	Tourism and local community
Respondent 3	Sargassum management
Respondent 4	Environmental consultant
Respondent 5	Local community and volunteer Sargassum clean-up
Respondent 6	Sargassum management – coordination
Respondent 7	Sargassum management - disposal
Respondent 8	Local community and fisheries
Respondent 9	Tourism
Respondent 10	Tourism and local community
Respondent 11	Sargassum management – disposal and collaboration

3.2 Multi-Criteria Analysis

Multi-criteria Analysis (MCA) is a useful decision making tool which can be used to evaluate and compare different options (such as waste management strategies) by assessing how various criteria perform within each option. The criteria aim to capture the full range of complexities associated with different options, focusing not just on monetary value (as in traditional cost-benefit analyses) but also on qualitative and quantitative factors such as environmental impact, social equity, and enhanced resilience. The tool can effectively be applied to areas and sectors where important social and environmental impacts cannot be expressed in terms of monetary values (Nautiyal and Goel, 2021). The key components of an MCA are defining the objectives, the options, the criteria, and having a scoring and weighting exercise take place. In the context of this research, these key components were applied in the following way:

- **Objectives:** The overarching goal. In this instance, we identified the overarching goal to be sustainable waste management of organic waste on the island of Bonaire, which included Sargassum and other organic waste.
- **Options:** These were defined as the alternative organic waste management strategies that were developed in the BonCirc project by Lanting et al (forthcoming). These are the following four strategies (see Section 5.2) that combine different waste management innovations: Composting, Anaerobic Digestion, Black Soldier Fly Larvae.
- **Criteria:** These are the metrics that were used to assess the performance of the strategies, encompassing social, environmental and economic impacts (e.g. food security, dependency on imports, circular economy).
- **Scoring:** This is evaluating how well a certain criterion performs under a specific option (or waste management strategies). Quantitative and qualitative assessments can be used for this, with certain data acting as an indicator on how to assess the interaction e.g. dependency on imports could use the data on fertiliser substation or diesel substation for each strategy.
- **Weights:** Weighing the relative importance of each criterion based on stakeholder consultation, or on a specific scenario explored (e.g. are social impacts deemed more important than economic).

The objective of the MCA was to evaluate the various waste management strategies' and compare them to each other using various criteria. The tool of MCA encompasses a variety of approaches to compare and evaluate strategies, interventions and/or strategies against multiple criteria. MCA is commonly used in debates on waste management strategies. For example, Lombardi and Todella (2023) reviewed 58 papers in which a multi-criteria analysis of agricultural waste management strategies was presented. This review illustrates that there are various types of MCA, differing in the criteria, scoring and/or ranking of criteria. The majority of studies reviewed include stakeholders in the assessment process. Often, before applying an MCA, a series of interviews and/or surveys are conducted with selected stakeholders, which can serve both in the identification of criteria and possibly in the weighing of criteria.

The data and criteria to use in MCA can come from a variety of sources. Life Cycle Assessment can be one source, e.g. Milutinovic et al (2017) evaluated four waste management strategies, using six LCA impact categories (Abiotic depletion potential, global warming potential, human toxicity potential, photochemical oxidation potential, acidification potential and eutrophication potential) as environmental indicators. However, when other impacts such as social and/or economic needs to be taken into account, an MCA often requires the use of various data sources and expert judgement.

When it comes to the scoring and ranking, Garcia-Garcia (2022) identifies the following main approaches to MCA:

- The **Analytical Hierarchy Process (AHP)** is a decision-making framework that evaluates alternatives by structuring complex problems into hierarchies, assigning relative weights to criteria, and using pairwise comparisons to determine the best option.
- **Multi-Attribute Utility Theory (MAUT)** is a decision-making framework that evaluates alternatives by quantifying preferences across multiple criteria, assigning utility values, and aggregating them to determine the most optimal choice based on overall utility.
- **Outranking procedures** are decision-making methods that compare alternatives pairwise based on multiple criteria, establishing preference relations rather than absolute rankings, allowing decision-makers to identify the best options without requiring full compensability between criteria.
- **Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)** ranks alternatives by measuring their geometric distance from an ideal best and worst solution, selecting the option closest to the ideal and farthest from the worst.

In this study, the Multi-Attribute Utility Theory (MAUT) was used, based on the necessity for a decision-making framework that moves beyond ordinal ranking. MAUT can achieve a cardinal measurement of true value. MAUT is initially more demanding initially, requiring quantification of all scores, but comes with complete transparency, creating a clear and transparent reasoning from raw data to final recommendation. This transparency, combined with its ability to produce a complete and rational ranking based on a true interval scale, makes MAUT the most robust and justifiable choice for comparing waste management strategies.

The main advantages of a MCA study are that it allows for a wide range of criteria which might be both quantitative and qualitative, which is beneficial when considering the socioeconomic impact of different waste management options. The methodology enables various stakeholders to express their preferences and priorities for different criteria, enhancing collaboration and leading to more holistic, informed and well-rounded decisions. The methodology provides a useful structured framework to compare and evaluate different alternative waste management options, using criteria that might not have quantified impacts (as would be needed in a cost-benefit analysis for example).

The main disadvantages of an MCA study are that the process and results can be fairly complex and therefore challenging to disseminate and communicate to those unfamiliar with the process. This can impact how the results are understood by stakeholders. The weighting of criteria—and even the selection of criteria—is assessed in part through subjective judgments, which can lead to potential inconsistencies in the results. The indicators used to assess each criterion may include some quantitative data; however, in cases where such data are unavailable, a qualitative evaluation based on literature and expert judgement is applied. The main purpose of the tool is to compare different waste strategies, whilst assigning weight to the criteria that stakeholders consider most important.

The evaluation criteria are outlined in Section 5.1, based on a comprehensive review of the challenges Bonaire faces due to Sargassum beachings and an overcrowded landfill, where the convergence of various waste streams leads to greenhouse gas emissions, nutrient leakage and eutrophication of natural environments and coastal habitats. These challenges can be mitigated with waste management strategies.

3.3 Data Collection

Various data sources were used in this assessment of the environmental, social and economic impact of organic waste management in Bonaire. The following data collection methods were used:

- 11 Interviews with local stakeholders in Bonaire were conducted during field work in Bonaire and site visits to landfills (see Table 1 for their roles).
- A desk review was carried out looking into existing literature and policy documents that are publicly available.
- Results from the different work packages in the wider BonCirc group were used, particularly results from WP5 and their Circularity Analysis Tool (CAT) and their Techno-Economic Assessment (TEA) (Lanting et al., forthcoming). Output from their work was used within the MCA study.
- Expert judgement was used in parts of the MCA where qualitative indicators were required. This included consultation with members of the consortium through their work on previous work packages, and discussions in consortium meetings. Input from academic and grey literature and policy documents further helped to support the qualitative assessment made by the research team.
- A separate small survey was carried out within the project partners in Bonaire in May 2025 to collect feedback on the weighting of the criteria for the MCA analysis. The respondents work in agriculture, water, and project development in Bonaire and are affected by a change in waste management strategy. Five responses were provided in this survey with the following roles: senior manager, advisor and entrepreneur. Validation from these same experts was sought for the selection of criteria and the indicators used.

4 Preventing the beachings of pelagic Sargassum has socioeconomic benefits

This chapter provides insights into the socioeconomic impacts of increased Sargassum influxes on Bonaire and how these are managed. Data and insights on the socioeconomic impact were collected during a site visit and a series of interviews conducted in the field in 2023 (see above).

4.1 Sargassum beachings have perceived negative impact on nature and companies on the eastern side of Bonaire

The prevailing theme of concern among the participants is the impact increased Sargassum influxes may have on nature. All respondents mentioned the impact frequent influxes have on nature in Bonaire, with a particular focus on mangroves, sea turtles, and seagrass beds. Further questioning about the socioeconomic impacts revealed a strong connection to nature, with respondents highlighting the costs of nature restoration due to Sargassum influxes, as well as the negative impact on tourism, which heavily relies on Bonaire's natural attractions (Figure 4).

The most impacted groups by Sargassum influxes were the managing organisations, as well as companies located on the eastern side of the island, including restaurants, accommodations, and coastal attractions such as tours and water activity operators.

The socioeconomic and ecological impacts extend across the entire lifecycle of Sargassum. At the beginning there are impacts at sea, with documented death of seagrass beds, causing fishing boats and their lines to tangle, and disrupting popular marine activities on Bonaire such as windsurfing and diving. These concerns are consistent with UNEP (2018), which reports that Sargassum influxes can damage mangroves and seagrass seedlings, disrupt fishing operations, reduce access to fishing areas, and increase fish mortality (Robledo et al., 2021). Once the Sargassum reaches the coast, reported impacts include an unpleasant appearance and the transport of plastics and dead organisms within the Sargassum itself. If left unattended for more than a day, the Sargassum starts to decompose, which causes a stench surrounding the island that is further carried with the wind throughout neighbourhoods in Bonaire. During manual collection, the use of tools such as pitchforks and shovels brings people into close contact with Sargassum, raising concerns about human health risks from gases released during decomposition. In addition, the use of heavy machinery to remove Sargassum can lead to the contamination of sand and coastal erosion.

Concerns were reported toward the end of the cycle, regarding the alternative use and disposal of Sargassum. Finding alternative uses for the Sargassum can be challenging due to its high heavy metal content, which can affect human health, as well as the potential use as animal feed, fertiliser or construction material. Respondents expressed their concerns that there was a potential lack of sufficient research on the risk of using Sargassum in these different domains on the island. Some research already highlighted the potential impact of Sargassum decomposition on human health, due to the production of hydrogen sulfide and anhydrous ammonia, which can irritate the upper airways and cause headaches, nausea and other health effects (UNEP, 2018; Chávez et al., 2020; Resiere et al., 2020). The disposal of Sargassum at the landfill allows for a certain extent of control in terms of having a designated location without risk of spreading and mitigating the stench. However, it is unsure if this disposal method is adequate, as interviews revealed that the landfill is located near the ocean and may be susceptible to leaching of dangerous compounds from the heavy metals, which can be released in higher concentrations during decomposition.

Finally, some respondents recollected memories of health concerns occurring during manual Sargassum clean-ups in Punto di Kalbas, Bonaire. This was supported by participants expressing apprehension about volunteering for Sargassum removal, due to concerns about potential health effects. Economic losses have

occurred on the island due to the need to invest in mangrove and seagrass replanting, in addition to other nature restoration efforts that have since been affected by Sargassum influxes.



Figure 4 *Sargassum accumulation at the east coast of Bonaire*
Source: Mr J. Driegen.

Despite the prevailing pattern of the negative impacts Sargassum has on the environment, it is worth noting that a number of respondents expressed scepticism regarding the severity of damage Sargassum causes to ecosystems. This assumption was reinforced by the suggestion that the impact of Sargassum on the ecosystem may be less severe than commonly believed, with influxes compared to forest fires which may seem damaging at first sight but which can have beneficial effects.

When discussing the socioeconomic impacts on tourism, respondents gave conflicting responses due to the distance between the Sargassum-prone eastern side and the tourism-focused western side of Bonaire. While some believe tourism is minimally affected due to the distance between affected coastlines and the main tourism areas, most respondents feel it is heavily impacted because of Sargassum's detrimental effects on nature, which is central to Bonaire's nature-based tourism. Those who hold this view argue that tourists are generally unaware of the situation because tourism takes place on the opposite side of the island from the Sargassum-affected areas. Most diving and water sport activities occur on the western side of the island, with only a small percentage of tourists visiting the Sargassum-affected areas. As a result, respondents felt there is insufficient evidence to suggest a significant impact on tourism in Bonaire.

However, there are those that argue that as Sargassum damages the natural ecosystem and nature, it therefore damages tourism in Bonaire. This is consistent with Chávez et al. (2020), who found decaying Sargassum reduced tourism activity by 35% due to the unpleasant smell and unattractive appearance (Robledo et al., 2021). Respondents also highlighted that there was a decrease in those wanting to

participate in water activities such as kayaking, diving, and windsurfing. Sargassum limits the recreational activities on water and may even be dangerous in some cases, with the example given of affecting windsurfing speeds, potentially causing a loss of control. Another point is that, although tourism is mostly concentrated on the western side, the few companies located on the eastern side are reportedly affected by economic losses during Sargassum influxes, additional labour for Sargassum removal, and investments in heavy machinery to assist with collection. This disruption of activities not only affects tourists, but the recreational activities and employment of the local community in this sector as well. Additionally, decomposing Sargassum releases an unpleasant odour that can affect both tourists and locals in the surrounding areas.

The interviews revealed differing perspectives surrounding the impact on the local community. Those who believe influxes impact the local community, attribute this to the smell of decomposing Sargassum and the potential health effects of influxes. Affected neighbourhoods were said to be Antriol, Nawati, Noord Saliña, Hato, Buena Vista, and Playa Pabou. Interviews indicated that part of the local population in Bonaire is less concerned with Sargassum, climate change, or nature conservation, and instead prioritises other socioeconomic issues such as poverty and inequality.

Some benefits that Sargassum provides to ecosystems were recognised in some interviews, such as in the case of fishing. In normal amounts, Sargassum made certain species easier to access. However, what was once seen as beneficial, is now a nuisance. Sargassum clogs motors and pipes, disrupting fishing activities, which forces fishermen to take additional measures to adapt during influxes. It was reported that fishermen have experienced delays and, on several occasions, were unable to navigate through Sargassum with their boats. The respondents attribute shifting conditions within ecosystems in Bonaire to a combination of multiple factors, not necessary Sargassum. There are certain species of fish that are affected but it is unknown whether it can be attributed to only Sargassum or other factors, such as overfishing.

4.2 The ecological impact of Sargassum beachings is mostly seen in the mangrove areas

The aim of another study in the BonCirc project was to quantify the ecological impact of the recent massive Sargassum influxes on mangrove forest cover in the coastal bays of Bonaire (Mücher et al., 2024). A change detection analysis utilising Very High-Resolution (VHR) satellite imagery was performed to evaluate the changes in mangrove cover in two coastal bays (i.e. Lagun and Lac Bay) on Bonaire, attributable to recent coastal influxes of Holopelagic Sargassum brown algae. Results showed that in 2014, the total area coverage of mangroves in Lac Bay was 221 ha, of which 16 ha (7.2%) was lost in the period between 2014 and 2020.

However, based on the maps that showed where Sargassum accumulated within Lac Bay, only 0.6 ha (3.7%) of the total mangrove area that was lost between 2014 and 2020 could most likely be attributed to the direct impact of Sargassum influxes (i.e. the outer edge of the mangrove forest in the West of Lac Bay), while the remaining mangrove loss of 15.4 ha (96.3%) could most likely be attributed to run-off related sedimentation in the backwaters of Lac Bay. The total area coverage of mangroves in Lagun was 2.6 ha in 2014, of which 1.2 ha (46.2%) has been lost in the period between 2014 and 2020. Of the mangrove area that was lost in Lagun, 0.4 ha (33.3%) could most likely be attributed to the direct impact of Sargassum influx, while the remaining mangrove loss of 0.8 ha (66.7%) was most likely the result of run-off related sedimentation.

4.3 Sargassum management has changed in recent years

The main actors involved in the current management are reported to be STINAPA, Cargill, OLB, nature conservation NGOs such as Mangrove Maniacs, and operators of water sports. Cargill, a company that produces salt in Bonaire, resides within STINAPA borders and therefore works alongside STINAPA to manage influxes on company grounds, located at Pekelmeer, a RAMSAR site and breeding area for flamingos in Bonaire. Secondary actors who generally participate in disaster scenarios are the fire department, the police force, the Bonaire Hotel and Tourism Association (BONHATA) for communication purposes, and the European

Netherlands government. Respondents agree unanimously that organisations and communities living nearest influx locations are most affected, along with the management organisations of Sargassum due to the intensive labour and additional responsibilities.

A common theme emerged regarding how Sargassum is framed during discussions about its management. Several respondents expressed concern that presenting it as a problem to the public could scare tourists away, while also questioning whether Sargassum is truly a problem or only perceived as one, and suggesting that management should reflect this distinction. Under this theme, respondents raised concerns that framing Sargassum as a problem could affect the motivation of clean-up volunteers. On the other hand, some believe that Sargassum makes the impacts of climate change more tangible and visible, providing an opportunity to raise awareness of Bonaire's vulnerability and encourage greater community engagement and support for climate policies.

The former procedure of Sargassum clean-up was done by removing Sargassum manually using pitchforks, rakes, and shovels in what was described as a labour-intensive, lengthy process that takes a physical and mental toll on those executing the work. This has since changed in what respondents describe as a period of significant progression and adaptation for managing actors. This is said to be initiated in 2018, one of the worst years for Sargassum influxes. At the time, managing the influxes was complicated by uncertainty over which actors were responsible and how Sargassum should be framed. The first possibility was to view influxes as an 'episodic emergency', which falls under the responsibilities of the OLB. The second possibility was based on influxes occurring in locations within STINAPA's borders of management, and for this reason, the responsibility is of STINAPA. Eventually, STINAPA became the main actor responsible for Sargassum influxes, mandated by the OLB, which then serves as the central point for coordination and provision of the Sargassum Crisis Handbook.

In 2022, STINAPA was also able to obtain financial support from the OLB through the European Netherlands Government to accelerate their increased efforts, causing this year to be described as a turning point in Sargassum management. However, sufficient funding remains a critical concern when considering long-term management. Further advances occurred when the decision was made to mitigate the damage influxes are causing to mangroves. A channel was decided to be cleared to remove Sargassum from difficult to reach areas and install booms. For this reason, STINAPA removed a certain amount of mangroves to ensure physical accessibility. Data provided during interviews shows a significant change in the effectivity of Sargassum management, with the example of removing 5% of Sargassum in 2022, to removing up to 70% of Sargassum in February 2023. Although this improvement was only possible with the clearing of mangroves, it is recorded to have caused a mixed reception throughout the local community. Further measures STINAPA was able to implement were boom installations that prevent the spread of Sargassum on the water, and allow for easier collection at three separate locations that regularly receive influxes. STINAPA monitors Sargassum patterns with satellite imagery and creates regular reports to maintain open communication channels with other stakeholders identified as the OLB and Cargill. STINAPA's actions have not gone unnoticed by the community. All respondents mention STINAPA as the main actor in Sargassum management and to some extent acknowledge the measures taken to manage Sargassum. For example, respondents express that their initial impression was that it started as a trial-and-error method of learning that eventually became an efficient and improved way of management, and other respondents referring to the actions undergone since 2018.

In 2023, Sargassum removal followed a structured procedure. Forecasting using satellite imagery helps guide removal before it reaches the shore, with booms directing Sargassum to locations where it can be more easily collected. Heavy machinery is then used to collect it, after which it is transported to the landfill for disposal. If landfill disposal is not possible, Sargassum is taken to one of three designated nearby dumping sites.

The current procedure was tested during a moderate influx in early 2023. However, the incoming amounts do not compare to the mass landings that occurred in, for example, 2018, which leaves the efficacy of this method still unknown when it comes to larger amounts.

On the eastern coast, Sargassum is removed along the shore, with most of the work reportedly carried out by employees, volunteers, and tourists. Depending on the volume of the influx, Sargassum is sometimes removed manually by collecting it and placing it on water sports boards, then disposing of it at a nearby dump site away from the shore. Respondents noted the importance of collective action and shared responsibility for clean-ups, with some companies investing in heavy machinery to assist with removal along the coast. However, critical comments were raised about the use of heavy machinery, as it can cause environmental damage, including the death of organisms in the sand and erosion from the removal of large quantities of sand.

4.4 Sargassum management is still challenging

The main challenges for Sargassum management in Bonaire are said to be the volume, insufficient funding, equipment and machinery acquisition, and insufficient capacity. There are plans for executing trials of other tools that may be more efficient and environmentally friendly for removal, given that funding allows for this. The development of Sargassum management is described as a very costly undertaking, estimated to cost thousands of dollars a day. Furthermore, stakeholders indicated that 2023 has not brought sufficient Sargassum to be able to ensure maximum return on investment. This is said to require at least 10 days' worth of Sargassum influx. In the first months of 2025, the reported influx of Sargassum was very high.⁷

The context of Bonaire is seen as a special case under respondents. This is because the size of the island gives the impression that Sargassum is a disaster risk, although it is not enough to merit any significant investment because there is insufficient Sargassum in comparison to the volumes documented in Mexico. Further, Bonaire is said to be a unique landscape, requiring specific adaptations, and therefore cannot be approached with broad applications from other areas. A result of this is that it makes applying measures more difficult in terms of cost, feasibility, maintenance, and the decentralised position of the island.

The preferences in further progression for Sargassum management lie toward an approach that collects Sargassum on water, preventing it from reaching the shores, especially enclosed bays. Another aspect of management that was mentioned was increased collaboration, naming regional collaboration with Aruba, Curaçao, St. Maarten, and others affected within the Wider Caribbean Region (WCR), such as the French Caribbean. Other respondents were unsure whether large-scale collaborations may be feasible within this context due to the heterogeneity of destinations within the WCR.

Further mentions were for increased support from the European Netherlands. When asked to elaborate, respondents mentioned providing funding and assisting with material procurement. According to respondents, expenses during what is described as a 'normal season' of influxes is approximately USD 100,000-150,000. Further financial losses were reported by tourism-based organizations, including restaurants, water-activity operators, and accommodations near Sargassum-affected areas, due to decreases in reservations and occupancy. On the other hand, respondents noted that economic loss is not the only outcome. Some beneficiaries of frequent Sargassum influxes include researchers, machinery and equipment suppliers, shipping companies, and individuals employed through STINAPA's expansion.

Adaptation recommendations for tourism depend on whether Bonaire chooses to continue developing the sector. Some respondents prefer to reduce dependence on tourism and therefore do not support adapting tourism-related activities. Others believe diversification of tourism may be necessary, emphasising inland and cultural aspects of tourism as alternatives for the current main attraction of nature. Other adaptation measures incorporating both tourism and the local community are to designate specific areas for leisure away from Sargassum-prone coastlines and installed booms. The options for exportation were different among respondents, with the majority against exportation, wanting to keep the processing of Sargassum local. Respondents noted that increased communication and awareness raising within the local community may help motivate volunteers and educate the community regarding alternative uses of Sargassum. Respondents provided conflicting views on volunteering for clean-ups. Volunteer efforts play a key role in Sargassum removal and are conducted exclusively by hand, since operating machinery requires a license.

⁷ <https://www.bonaire.nu/nieuws/natuur/75865/opnieuw-grote-hoeveelheden-sargassum-aangespoeld-op-bonaire>

Nevertheless, it is expressed that reliance on volunteering may not fare well in future approaches as volunteer fatigue may occur. The manual clean-up of Sargassum is known to be labour-intensive, unpleasant due to the smell, and may affect human health in severe cases. Positive aspects of volunteering were reported to offer an increased sense of community by bringing inhabitants together for the common goal of helping their island. Furthermore, community involvement presents the impacts of climate change in a more tangible, visible, and direct way that offers the opportunity to spread awareness of Bonaire's vulnerability to climate change. Although several examples of an alternative use for Sargassum were named, such as construction materials and biofuel, all expressed further research needs to be conducted before considering the implementation.

5 Organic Waste Management Innovations and strategies

In the current situation, the Sargassum that is collected from the beaches is landfilled. Given the limited capacity for landfilling and the desires to make more meaningful use of the biomass (Sargassum and other organic waste), three alternative waste management innovations were investigated within the project, black soldier fly larvae; anaerobic digestion, composting alongside some incineration. Four different waste management strategies were then developed which combine these three waste management innovations, as defined in Section 5.2.

5.1 Innovations for organic waste management are developed

5.1.1 Black Soldier Fly larvae

Black soldier fly larvae (BSFL) can be cultivated to be used as protein and nutrient in animal feed and break down a variety of organic wastes such as chicken manure. During the growth of the larvae, the organic waste is turned into frass (or the residue droppings of BSFL), which in turn can be used as a fertiliser. The BSF larvae themselves can be sold as a protein source for other livestock. Currently, the use of larvae grown on chicken manure as chicken feed is being investigated in many parts of the world. However, this approach is not yet accepted by European legislation, due to possible safety risks regarding the content in medicines or other contaminants (Bruins et al., 2024). If used properly, the BSF larvae can effectively repurpose 'dirty' organic waste such as cattle, poultry and pig manure, kitchen and household waste, and sludges (Surendra et al., 2020) into feed ingredients and fertiliser. BSFL cultivation potential on Bonaire is determined by the amount of organic waste available to use and the application. The availability of food waste and other organic wastes besides (chicken) manure on Bonaire is relatively low, since these streams are already directly used as feed.

5.1.2 Anaerobic digestion

Anaerobic digestion is a biological process whereby microorganisms decompose various biomass and organic waste streams under anaerobic conditions, generating energy-rich biogas (Rehman et al., 2019). It converts waste into biogas — a renewable mix of methane and carbon dioxide — and digestate which is a nutrient-rich residue. This digestate then has the potential to be used as fertiliser for agricultural purposes (Rehman et al., 2019). This process reduces waste volume, mitigates greenhouse gas emissions, and generates sustainable energy and fertilisers, promoting circular economy principles. The creation of a biogas facility to treat poultry manure was discussed before.⁸ The construction of a biogas production facility would require additional investment if it was to be carried out on Bonaire, learning from other islands that have successfully built such facilities. One benefit of anaerobic digestion is that the waste streams do not need to be dried, saving time and space.

5.1.3 Composting

The use of Sargassum as composting is an organic waste management option that is considered for Bonaire. Composting is the controlled conversion of organic waste under aerobic conditions and with the assistance of microorganisms, into products that can be used as fertiliser and other soil amendments (Ayilara et al., 2020). As the heavy metal content of Sargassum on its own is too dangerous to be used in composting, creating a mix with other organic waste streams such as food waste, chicken manure, and other waste is needed to dilute the mixture and bring the heavy metal content below a certain threshold. Sewage sludge from waste water treatment and other organic fraction of company and household waste can also be used in the mixture to dilute the Sargassum. This threshold would then need to be backed and supported with Dutch legislation. Economies of scale are needed for this solution, as large amounts of other waste streams must be

⁸ <https://antilliaansdagblad.com/nieuws-menu/17203-biogasinstallatie-voor-kippenmest>

combined to dilute the heavy metals in Sargassum. The waste requires little energy to treat because it is self-heating, which further reduces costs. Seasonality is also a concern, as Sargassum influxes vary throughout the year, affecting the availability of other wastes needed for dilution. Additionally, although dilution can reduce heavy metal content below regulatory thresholds, using Sargassum in this way remains controversial due to the residual heavy metal content.

5.2 Four strategies are further described

The BonCirc project developed four strategies for managing the organic waste stream treatment in Bonaire, and determine their circularity within the value chain. Lanting et al (forthcoming) investigated the following strategies:

- Strategy 1: Composting & incineration
- Strategy 2: Insects, composting & incineration
- Strategy 3: Anaerobic digestion, composting & incineration
- Strategy 4: Omnivorous anaerobic digestion & composting.

5.2.1 Strategy 0: Current situation

In the current situation, organic waste streams including Sargassum and other organic waste largely end up in a landfill. The largest landfill in Bonaire is the landfill of Selibon which is situated within the Lagun district, and most waste streams largely end up in the landfill, including Sargassum, organic waste and other waste streams.

Some organic waste which is not landfilled is used for animal feed (see Figure 5), but the issue with Sargassum for example is that the heavy metal content makes this impossible. The landfill causes several environmental and social impacts, especially for residents of the Lagun district, who must contend with vermin, strong odors, and illegal or accidental burning of waste. Some illegal and/or accidental burning of landfilled waste takes place on the island, for example at the Lagun site (Slagt, 2024),⁹ which in turn leads to leakage of water used to put out the fires. As the main landfill in Bonaire is situated next to the sea, nutrient and heavy metal leakage, as well as leakage from water after a fire, ends in the sea, thereby negatively impacting the natural environment and further impacting the locals' quality of life. The landfill contains not only organic waste and Sargassum but also other waste streams, making it very large and odorous, which further affects the quality of life for local residents.



Figure 5 Donkeys fed with garden waste in Bonaire
Source: Mr J. Driegen.

⁹ [Eerste Kamer der Staten-Generaal](#)

For the purposes of the strategies developed by Work Package 5 (WP5) of the BONCIRC project, and thereby used within the MCA and socioeconomic analysis, the base case scenario assumes all waste is landfilled.

5.2.2 Strategy 1: Composting & incineration

In this strategy, the sewage sludge and Sargassum are separately dried and incinerated due to their heavy metal content. The other organic waste flows (chicken manure, pruning waste and organic waste) are brought together for composting.

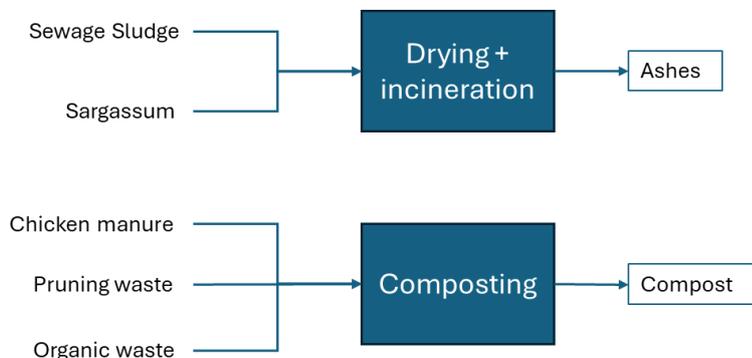


Figure 6 Waste Management Strategy 1

5.2.3 Strategy 2: Insects, composting & incineration

In this strategy, the sewage sludge and Sargassum are dried and incinerated. The chicken manure is used for the growth of Black soldier fly larvae (BSFL). BSFL are sold as feed, the frass is composted together with the pruning waste and other organic waste.

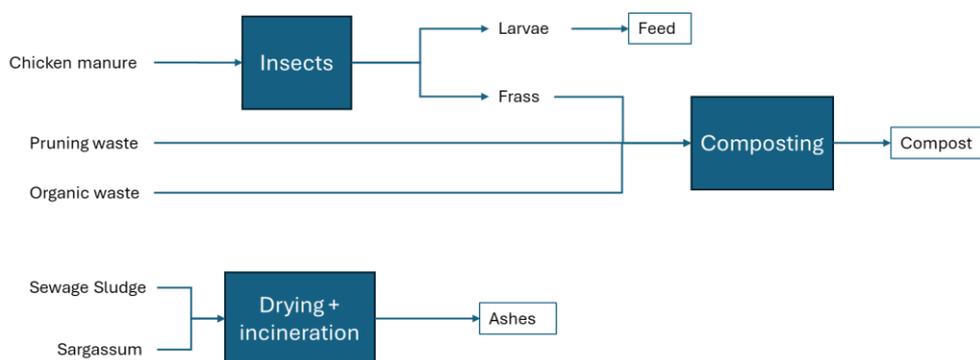


Figure 7 Waste Management Strategy 2

5.2.4 Strategy 3: Anaerobic digestion, composting & incineration

In this strategy, the sewage sludge and Sargassum are not digested but are separately dried and incinerated. The other two organic waste flows (chicken manure and organic waste) are brought together for anaerobic digestion. The biomass is anaerobically digested, resulting in the production of biogas and digestate. The digestate can be further composted. The digestate can be further composted.

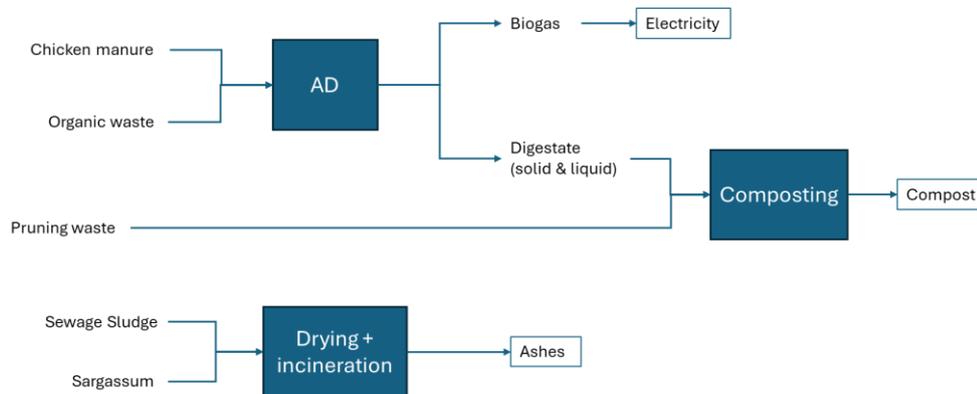


Figure 8 Waste Management Strategy 3

5.2.5 Strategy 4: Omnivorous anaerobic digestion & composting

In this strategy, various organic waste flows are brought together for anaerobic digestion. This includes sewage sludge, a part of the Sargassum, chicken manure and other organic waste. All biomass is anaerobically digested, resulting in the production of biogas and digestate. The digestate can be further composted. The surplus Sargassum is incinerated to keep heavy metal levels in compost below the allowed limits.

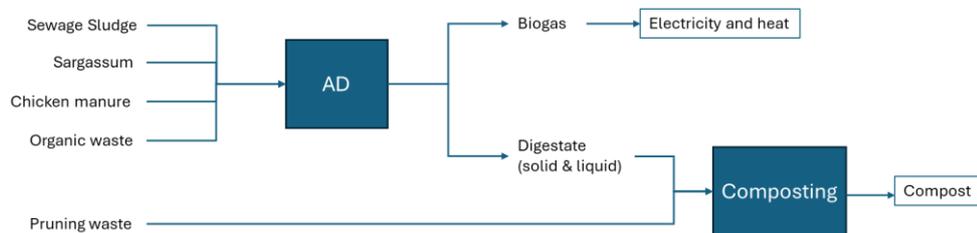


Figure 9 Waste Management Strategy 4

These four alternative waste management strategies were considered more sustainable than the current practice of landfilling, which carries a high risk of accidental burning—an illegal activity that contributes significantly to air pollution

6 Evaluation of the impact of waste management strategies

In the project, four alternative waste management strategies (scenarios) were developed under WP5, in consultation with other project members. A Multi-Criteria analysis was selected as the best methodology to evaluate the impact of the defined waste management strategies across a variety of social, economic and environmental criteria. The following section begins with the selection of appropriate criteria for the MCA, based on the environmental and socioeconomic challenges on Bonaire previously described in Chapter 2. Section 5.2 and 5.3 present the results of the MCA, followed by recommendations and conclusions.

6.1 Selection of criteria

For the MCA, the first important step was to develop a set of criteria that was well aligned to the underlying objectives and with the data available. For high-level policies and strategies, existing frameworks (such as e.g. the Sustainable Development Goals) can be used to structure the formulation, review and selection of criteria. In other cases, brainstorming based on expertise and literature can provide the basis. Given the focus of BonCirc on a specific topic (organic waste management strategies) in a specific context (Bonaire), we opted for developing our own set of criteria.

The first step was to create a long list of criteria which we had identified and evaluated against several aspects. This list for assessing waste management strategies was developed based on a literature review, particularly drawing from Achillas et al. (2013), who reviewed studies using MCA to evaluate solid waste management strategies. To select the most relevant criteria for BonCirc, the following three aspects were taken into account:

- Aspect 1: Relevance for evaluation of waste management strategies, also taking into account the particularities of waste management on Bonaire
- Aspect 2: Relevance for achieving the policy objectives of Bonaire (described in Chapter 2)
- Aspect 3: Data availability as this determine the possibilities of given a reliable score.

Each criterion was evaluated looking at these three aspects, with scores ranging from -2 (not relevant at all) to +2 (highly relevant). The sum of scores was then calculated in order to aid the final short list selection of the most relevant criteria to use in the MCA. To see the long list of criteria and their associated score, see Appendix 2.

Based on the evaluation of potential criteria, the following criteria were selected and further described to fit to the objective of the BonCirc project (see Table 2).

Table 2 Selection of criteria for the MCA

Category	Criterion	Description
Social	Food security	The extent to which the waste management can contribute to the production of food to Bonaire (direct food or via fertiliser/compost)
	Equity and inclusion	The extent to which the waste management strategy contributes to the creation of income and opportunities for a diversity of stakeholders
	Contribution to quality of life on Bonaire	The extent to which the waste management strategy improves quality of life on Bonaire, including but not limited to reduction of waste, improved local environment (excluding economic factors – see below)
Economic	Investment Costs	The costs and prices to operate the waste management strategy
	Reduced dependency on imports	The extent to which the waste management strategy reduces the need import goods/materials
	Revenue	The extent to which the waste management strategy can be taken up by commercial, market parties (i.e. less dependent on full and/or continued government support)
Environmental	Contribution to circular economy	The extent to which the waste management strategy contributes to closing of nutrient cycles on Bonaire
	Carbon Footprint	The carbon footprint of the waste management strategy
	Protection of nature	The extent to which the waste management strategy (directly or indirectly) contributes to protecting and improving the quality of nature and biodiversity on Bonaire
	Pollution	The impact of the waste management strategy on air, water, soil, and noise pollution levels.

6.2 Multi-criteria analysis of the different organic waste management options

6.2.1 Evaluation of the strategies

For each identified criteria, the MCA used various indicators to measure how the specific criteria performed for each strategy. Where possible, quantitative data were utilised with outputs from WP5's TEA and CAT studies providing useful indicators for certain criteria. Where quantitative data for each strategy were not available, a qualitative assessment was carried out using expert judgement and outputs from a desk review of existing policy documents and other WP deliverables. A scale from -- to ++ was used, where a '--' indicated a negative relationship between the criteria and the strategy, and a '++' indicated a positive one. For example, for the criterion protection of nature, a '+' means that the waste management solution will partially contribute to the protection of nature on the island, while a '++' means that it has a stronger impact. Table 3 outlines the four waste management strategies (defined by WP5) and the data used in the final MCA (or the qualitative assessments made through expert judgement).

Table 3 Evaluation of the strategies

Criteria	Strategy 0	Strategy 1	Strategy 2	Strategy 3	Strategy 4
	Current situation	Composting & incineration	Insects, composting & incineration	Anaerobic digestion composting & incineration	Omnivorous anaerobic digestion & composting
Food security	+/-	++	++	+	+/-
Equity and inclusion	+/-	+	+	+	+/-
Contribution to quality of life on Bonaire	+/-	+	+	+	+
Investment Costs (million \$/year)	0	2.0	2.1	3.4	3.8
Reduced dependency on imports (Fertiliser substitution tonne/year, diesel substitution m ³ /year, feed substitution DW ton/year)	0	400	446	513	551
Revenues (million \$/year)	0	0.24	0.29	0.31	0.36
Contribution to circular economy	0%	3%	4%	7%	10%
Carbon Footprint	+/-	+	+	+	+
Protection of nature	--	++	++	++	+
Pollution (heavy metals)	Yes (--)	No (++)	No (++)	No (++)	Yes (--)

6.3 Social Criteria

6.3.1 Food Security

This criterion considers how much the waste management strategy can contribute to the production of food in Bonaire, either directly through food generation or indirectly through increased fertiliser or compost production. All three main strategies produce compost as a byproduct of organic waste management. As more compost becomes available for use in agriculture, the added organic matter can improve soil fertility and productivity (FAO, 2011; Lal, 2004). Therefore, across all four waste management strategies a positive increase in food security is identified. Since Strategy 1 (composting) shows the greatest potential for increasing compost production, it is assigned a '++' for its strong positive impact on food security. Strategy 2 (BSFL) not only produces compost as a byproduct but also generates animal feed, further supporting food security. The process yields high-protein feed as well as organic frass, which can be used as fertiliser in agriculture. Strategy 3 (anaerobic digestion) is assigned a '+' due to the byproduct of compost whereas Strategy 4 (Omnivorous anaerobic digestion) is deemed to potentially increase/decrease food security in Bonaire. Despite composting being a byproduct, the heavy metal content of products means that it is not safe to use in agriculture. The mixture of the compost content with other organic waste might dictate its impact on food security, but under current Dutch law, it is not allowed that a component of the mixture does not meet the standards (Rapportage Nederlands mestbeleid, 2021).¹⁰

6.3.2 Equity and Inclusion

This criterion considers the extent to which the waste management strategy contributes to the creation of income and opportunities for a diversity of stakeholders. Composting is a largely accessible practice and can help to engage local communities to participate as not much training is required (Suryani et al., 2025), and it can further contribute to farming, gardening and other similar activities. Since all four waste management strategies produce compost as a byproduct, they are considered to improve equity and inclusion on Bonaire compared to landfilling, and are therefore assigned a '+'. The use of an anaerobic digestion plant does not

¹⁰ https://www.eerstekamer.nl/overig/20220707/nederlands_mestbeleid_2021_41_p/document3/f=/vluugd52xiud_opgemaakt.pdf

provide many employment opportunities, with only a small number of jobs expected to be created (such as 3),¹¹ and the centralisation of a specific waste management system means equitable community participation is less prominent. Composting remains still labour-intensive work and therefore can help to create job opportunities. BSFL has the potential to create new green jobs in the insect farming, and feed and frass production and marketing, but the jobs would be highly specialised and require specific knowledge (Van Huis & Oonincx, 2017). As all four waste management options do not necessarily have the potential to create a large number of equal opportunities within Bonaire compared to the current practice of landfilling, no strategy was assigned a '++'.

6.3.3 Contribution to Quality of Life

This criterion assumes that there is a general increase in quality of life across the three main strategies due to a reduction in landfill waste. If Sargassum is effectively collected and treated, locals would no longer have to contend with its negative impacts on beaches, such as unpleasant odours (Chávez et al., 2020; Liranzo Gómez et al., 2021). A '+' was therefore assigned across each strategy for this purpose. The four waste management strategies also produce compost as a byproduct, offering benefits such as enhanced food security, opportunities for community involvement (e.g., community gardening), and increased biodiversity on Bonaire (Jurado et al., 2014).

6.4 Economic Criteria

6.4.1 Investment Costs

This criterion refers to the cost and prices to set up and operate the waste management strategy. The TEA carried out by WP5 calculated the investment costs for each waste management strategy, and these values were used as the main indicator for investment costs. The values used are the total CAPEX in million dollars per year. Composting remains cheaper in terms of infrastructure required, with the main costs coming from labour, land required and any equipment. However, anaerobic digestion has higher upfront costs, as systems must be built for biogas capture, energy conversion, and storage (Bajón Fernández et al., 2017). Reducing capital and management costs are a current target for the future development of biogas systems (Holm-Nielsen et al., 2009).

6.4.2 Reduced Dependency on Imports

This criterion refers to the extent to which the waste management strategy reduces the need for imported goods or materials. In this case, it was considered important to combine import substitution for various goods, as each serves a distinct purpose across the four waste management strategies. Fertiliser substitution (tonne/yr) was calculated across all four scenarios. For Strategy 2 (BSFL) the additional avoided product of feed was calculated (in tonne DW/year), as composting would help to offset some of these fertiliser imports (Zapałowska and Jarecki, 2024), and BSFL could help to provide a local solution to animal feed (Matheka et al., 2022) and some fertilisers, if the process could be scaled up large enough. For Strategies 3 and 4, the potential diesel substitution (m³/yr) was calculated, as biogas from anaerobic digestion could reduce diesel imports (Wierzbicki, 2012). For a breakdown of these amounts of product imports avoided for each scenario, see Lanting et al. (forthcoming).

6.4.3 Revenue

This criterion refers to the extent to which the waste management strategy can be taken up by commercial and market parties. Compost and BSFL products can generate market revenue, but this will be dependent on the demand, quality and community trust. Anaerobic digestion biogas also has a market value, which will in turn be dependent on infrastructure requirements in Bonaire (Ferdes et al., 2022). The value of total revenue was therefore used as the main indicator (million dollars per year), with the TEA carried out by WP5 calculating these costs.

¹¹ [Guidance for Government | ADBA | Anaerobic Digestion & Bioresources Association](#)

6.5 Environmental Criteria

6.5.1 Contribution to Circular Economy

This criterion measures how much a waste management strategy contributes to closing nutrient cycles on Bonaire and other resource cycles, thereby reducing waste and extending resource lifespans. Composting, BSF, and anaerobic digestion all support nutrient recovery, resource reuse, and local soil restoration (Ellen MacArthur Foundation, 2016). In WP5, a Circular Assessment Tool (CAT) was used to calculate the circularity of the different waste management strategies. For this MCA, CAT scores excluding pruning waste were used, as including it would disproportionately influence the circularity score due to the large volume of pruning waste available (Lanting et al., forthcoming).

6.5.2 Carbon Footprint

This criterion refers to the carbon footprint of the waste management strategy. Landfilling has a considerable carbon footprint due to the release of greenhouse gases like methane, that is emitted as anaerobic decomposition takes place (IPCC, 2021). As landfilling is reduced in the proposed four waste management strategies, there is an expected reduction in methane emissions, which has a 84 times greater global warming potential than carbon dioxide over a 20-year time scale (IPCC, 2021). Composting and the use of BSFL leads to some CO₂ emissions from biogenic sources, but these are expected to be minimal. Offsetting the methane emissions from landfilling results in a net reduction in the carbon footprint. Composting helps to store the carbon within the soil and, when properly managed, can also be applied to soils to help increase fertility and improve carbon sequestration (Lal, 2004). Gregorich et al. (2001) found that in general, the use of composting can enhance soil organic carbon (SOC) pools by more than the application of the same amount of nutrients from organic fertilisers (Lal, 2004). Anaerobic digestion produces biogenic CO₂ from biogas combustion, but replacing other fossil fuels with this biogas reduces the overall carbon footprint of waste management. The digestate byproduct also helps decrease the need for chemical fertilisers.

6.5.3 Protection of Nature

This criterion refers to the extent to which the waste management strategy (directly or indirectly) contributes to protecting and improving the quality of nature and biodiversity on Bonaire. All four strategies are considered to improve the protection of nature by reducing landfilling and the associated leaching that can harm soil and water quality, thereby benefiting biodiversity. Composting helps to improve soil health and adds important organic matter and nutrients to the soil, thereby also reducing the need for chemical fertilisers, which in turn could cause runoff (Lal, 2004). Composting piles, however, have to be well managed, as poorly managed piles could lead to nutrient runoff and attract pests. BSFL from Strategy 2 and Anaerobic Digestion from Strategy 3 and Strategy 4 require potentially less space than landfilling and composting, and these smaller footprints could reduce the impact on biodiversity and restore degraded land (Ali et al., 2023). Digestate produced through anaerobic digestion can further be used to restore degraded soils. Strategy 4 receives only a '+' compared to the other three strategies, which are assigned '++', due to the presence of heavy metals in its byproducts from processing Sargassum and sewage sludge.

6.5.4 Pollution

This criterion refers to the impact of the waste management strategy on pollution levels, which could include air, water, soil and noise pollution. Heavy metals are a good indicator of pollution due to their risk to soil and food safety (Alloway, 2013). In this instance, the indicator of heavy metal presence was used as a means to assess pollution levels across the four waste management strategies. All three main waste management strategies are able to remove the harmful heavy metal content through the processing of Sargassum and sewage sludge, thereby assigning them a '++', whereas Strategy 4 still has this harmful heavy metal within its byproducts thereby being assigned a '--'.

6.6 Normalisation of scores and preliminary results

The scores and evaluations of each waste management strategy was then normalised due to the mix of quantitative data and qualitative expert judgement assessments that had to be done during the indicator phase. By normalising the indicators onto a common scale, this enables a meaningful comparison across the criteria and is an essential step when conducting a MCA.

Where quantitative data were available to use, a min-max normalisation was applied which converted the values to a standard scaling from 0-1. For the qualitative assessments that were carried out on some of the social and environmental indicators, a discrete ordinal scale was used ranging from -2 (strong negative impact), through to 0 (neutral or no discernible impact), to +2 (strong positive impact). These values were then rescaled to align with the 0-1 normalised range that was also used for the quantitative data, where -2 mapped to 0, 0 mapped to 0.5 and +2 mapped to 1.

Initially, it was assumed that all criteria have an equal weight (10% of the total). The scores are presented in Table 4. After score normalisation, 1 represents the best performance and 0 the worst. Conditional formatting using a green-yellow-red scale was applied for readability, with green indicating the best performance (1) and red the worst (0).

Table 4 Normalised scores for the 5 strategies

Category	Criterion	Strategy 0	Strategy 1	Strategy 2	Strategy 3	Strategy 4
Social	Food security	0.00	1.00	1.00	0.50	0.00
	Equity and inclusion	0.00	1.00	1.00	1.00	0.00
	Contribution to quality of life on Bonaire	0.00	1.00	1.00	1.00	1.00
Economic	Investments	1.00	0.47	0.45	0.08	0.00
	Reduced dependency on imports	0.00	0.73	0.81	0.93	1.00
	Revenue	0.00	0.67	0.81	0.86	1.00
Environmental	Contribution to circular economy	0.00	0.30	0.40	0.70	1.00
	Carbon Footprint	0.00	1.00	1.00	1.00	1.00
	Protection of nature	0.00	1.00	1.00	1.00	0.75
	Pollution	0.00	1.00	1.00	0.50	0.00

The normalised scores presented in Table 4 reveal several insights. The current practice of landfilling organic waste in Bonaire is generally outperformed by the proposed strategies in all categories, particularly when considering social and environmental impacts. This is likely due to the reduction in leaching from the landfills affecting soil and water, and the reduction in greenhouse gas emissions like methane (CH₄) being of significant benefit to the natural environment and surrounding population. The increased products available from the other waste management strategies such as composting, feed and electricity generation, help to increase the associated social impact. The only criterion where the current landfilling strategy performs better than the 4 proposed strategies is investments. It is expected that the strategies with complex infrastructure and knowledge such as those involving anaerobic digestion plants, will be more expensive.

Strategies 1-3 perform consistently well across the social and environmental criteria, with the largest variety in scores seen in relation to the economic criteria. The following step in the assessment was to allocate different weights to each criterion and their scores were then aggregated. This calculated a total score for social, economic and environmental impacts, in addition to a total impact score. In this first step, all weightings were assigned an equal weighting of 10% (see Table 5).

Table 5 Aggregated weighted scores (equal weighting)

	Average Weighting				
	Strategy 0	Strategy 1	Strategy 2	Strategy 3	Strategy 4
Weighted Social Score	0.00	0.30	0.30	0.25	0.10
Weighted Economic Score	0.10	0.19	0.21	0.19	0.20
Weighted Environmental Score	0.00	0.33	0.34	0.37	0.28
Weighted Total Score	0.10	0.82	0.85	0.81	0.58

Following the equal weighting of the criteria, Table 5 shows that organic waste management strategies 1-3 have very similar scores, outperforming the current situation and Strategy 4. The outputs of the MCA show a negative impact closer to 0, and a positive one closer to 1. Strategies 1-3 perform better than the current situation across all three categories in terms of social, environmental and economic impacts. Strategies 1 and 2 have a higher social impact compared to the baseline and the other waste management strategies, due to the expected increase in products for agriculture such as composting and additional feed.

Strategy 4 performs worse in social impacts than Strategies 1-3, primarily due to lower scores in food security and equity and inclusion. This is caused by the presence of heavy metals in its compost, making it unsuitable for use in agriculture. The presence of heavy metals also lowers the environmental impact score for Strategy 4, despite it having the highest circularity score among the strategies. All 4 alternative strategies perform better in the environmental categories, due to the reduction in landfilling which has heavy environmental negative impacts associated with leaching and greenhouse gas emissions. The results of Table 5 are presented as a bar chart in Figure 10.

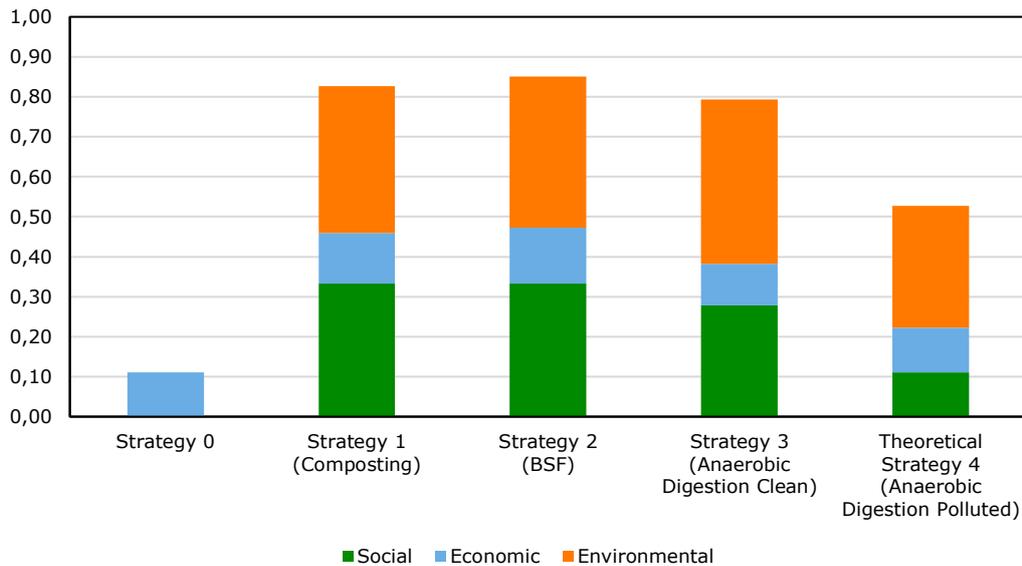


Figure 10 Results of the MCA with equal weighting as a bar chart

6.7 Results with different weightings (desk-based)

In this section, the robustness of these results was tested by varying the weightings. The researchers formulated three alternative weightings prioritising respectively the social, economic and environmental dimension (see Table 6). The prioritised category was weighted to account for 60% of the total, with the remaining criteria divided equally to sum to 100%. For example, to prioritise social impacts, each of the three social criteria was assigned a weight of 20%, while the remaining seven economic and environmental criteria were assigned 5.7% each. This process was repeated for a scenario which favours economic impacts, and one which favours environmental impacts.

Table 6 *Alternative weightings (formulated by the researchers)*

Category	Criterion	Equal ¹	Social	Economic	Environment
Social	Food security	10	20	5.7	6.6
	Equity and inclusion	10	20	5.7	6.6
	Contribution to quality of life on Bonaire	10	20	5.7	6.6
Economic	Investments	10	5.7	20	6.6
	Reduced dependency on imports	10	5.7	20	6.6
	Revenue	10	5.7	20	6.6
Environmental	Contribution to circular economy	10	5.7	5.7	15
	Carbon Footprint	10	5.7	5.7	15
	Protection of nature	10	5.7	5.7	15
	Pollution	10	5.7	5.7	15

¹ Results presented in section 5.2.

In Table 7 the results are presented under the three different weightings. The first table favours social impacts, so a higher weighting was assigned to the social criteria (as seen in Table 6). The second considers the economic impacts at a higher weighting, and the third has the environmental criteria weighted more highly. The purpose of changing these weightings under a social, economic and environmental 'scenario', allows priorities to be considered which can be beneficial for policymakers in Bonaire. For example, if the primary aim on Bonaire is to reduce the need for tourism and other imports, thereby increasing independency in Bonaire, then the policymaker would consider a higher weighting for the economic criteria.

Table 7 shows that strategies 1-3 again outperform the other two strategies, the differences with strategy 0 and Strategy 4 being even bigger. This outperformance is seen under a social, economic and environmental weighting. Strategy 4 performs better under an economic and environmental weighting. The difference between Strategy 4 and the other three strategies is closer under an economic weighting, likely due to higher revenues and estimated reduction in imports (of diesel and fertiliser).

Table 7 Aggregated scores under various weightings

	Social Weighting					Economic Weighting					Environmental Weighting				
	Strategy 0	Strategy 1	Strategy 2	Strategy 3	Strategy 4	Strategy 0	Strategy 1	Strategy 2	Strategy 3	Strategy 4	Strategy 0	Strategy 1	Strategy 2	Strategy 3	Strategy 4
Weighted Social Score	0.00	0.60	0.60	0.50	0.20	0.00	0.17	0.17	0.14	0.06	0.00	0.20	0.20	0.25	0.07
Weighted Economic Score	0.06	0.11	0.12	0.11	0.11	0.20	0.37	0.41	0.37	0.40	0.07	0.12	0.14	0.19	0.13
Weighted Environmental Score	0.00	0.19	0.19	0.21	0.16	0.00	0.19	0.19	0.21	0.16	0.00	0.50	0.51	0.37	0.41
Weighted Total Score	0.06	0.90	0.91	0.82	0.47	0.20	0.73	0.78	0.73	0.61	0.07	0.82	0.85	0.81	0.61

6.8 Results with different weighting (respondents based)

Various local stakeholders that are project members were invited to participate in the following step to help validate the evaluation of strategies, and provide their own weightings for the 10 criterion. Stakeholders were consulted during an in-person meeting in Bonaire, and additionally invited to provide rankings online. The form the stakeholders were provided can be found in Appendix 3. Five responses were recorded from local experts in Bonaire, and these stakeholders ranked the criteria using the following Likert scale: 1=very important, 2 = important, 3= neutral, 4= less important, 5= not important (see Table 8).

Table 8 Ranking provided by respondents

Category	Criterion	Respondent 1	Respondent 2	Respondent 3	Respondent 4	Respondent 5
Social	Food security	2	2	2	2	1
	Equity and inclusion	3	2	2	2	2
	Contribution to quality of life on Bonaire	1	2	1	1	2
Economic	Investments	3	3	2	2	1
	Reduced dependency on imports	2	3	2	1	2
	Revenue	2	3	2	3	2
Environmental	Contribution to circular economy	2	1	1	1	2
	Carbon Footprint	4	3	1	2	1
	Protection of nature	2	1	1	1	2
	Pollution	2	1	1	1	1

To use these data for the calculations in the MCA, two steps had to be taken. The ranking first had to be inverted, because a high priority (e.g. a rank of 1) should be reflected by a greater weight. The rules applied to this inversion can be found in Appendix 4. Notably, an original ranking of 5 (not important) was converted to 0, meaning no weight was assigned. The next step was normalisation, as shown in Table 9. Each criterion's rank was divided by the sum of all ranks and multiplied by 100.

Table 9 Weightings suggested by respondents

Criterion	Average	Respondent 1		Respondent 2		Respondent 3		Respondent 4		Respondent 5	
	Weight	Inverse ranking	Weight	Inverse ranking	Weight	Inverse ranking	Weight	Inverse ranking	Weight	Inverse ranking	Weight
Food security	10	3	11%	3	10%	3	9%	3	8.8	4	11.8
Equity and inclusion	9	2	7%	3	10%	3	9%	3	8.8	3	8.8
Contribution to quality of life on Bonaire	12	4	15%	3	10%	4	11%	4	11.8	3	8.8
Investments	8	2	7%	2	7%	3	9%	3	8.8	4	11.8
Reduced dependency on imports	9	3	11%	2	7%	3	9%	4	11.8	3	8.8
Revenue	9	3	11%	2	7%	3	9%	2	5.8	3	8.8
Contribution to circular economy	12	3	11%	4	14%	4	11%	4	11.8	3	8.8
Carbon Footprint	7	1	4%	2	7%	4	11%	3	8.8	4	11.8
Protection of nature	12	3	11%	4	14%	4	11%	4	11.8	3	8.8
Pollution	12	3	11%	4	14%	4	11%	4	11.8	4	11.8
Total		27		29		35		34		34	

The scores of each respondent using the average weight across all stakeholders can be found in Appendix 5. In Table 10, the aggregated scores are presented for the five respondents.

Table 10 Aggregated scores using the average weighting (five respondents)

	Average Weighting (five respondents)				
	Strategy 0	Strategy 1	Strategy 2	Strategy 3	Strategy 4
Weighted Social Score	0.00	0.30	0.30	0.25	0.11
Weighted Economic Score	0.09	0.17	0.18	0.17	0.18
Weighted Environmental Score	0.00	0.35	0.36	0.40	0.28
Weighted Total Score	0.09	0.82	0.85	0.82	0.57

Strategy 2 emerges as the most favourable, slightly ahead of Strategies 1 and 3 due to its higher social score. High rankings for contributions to quality of life and increased food security among respondents likely explain Strategy 2's advantage over Strategy 3. Strategy 4 scores higher than the baseline and has an economic score comparable to Strategies 1-3, likely because of high revenues and reduced dependency on imports. However, its social and environmental scores are lower. Overall, these stakeholder-weighted results are broadly consistent with the equally weighted results shown in Table 5.

6.9 Focusing on Strategies 1-3

Finally, we aimed to better understand the differences between Strategies 1-3. In the calculations above, these three scenarios have almost equal scores, likely because the baseline scenario (Strategy 0) performs very poorly, which obscures the relative differences among Strategies 1-3. For this exercise, the average weightings provided by respondents were used. Two criteria—contribution to quality of life on Bonaire and carbon footprint—show equal performance across Strategies 1-4 and were therefore omitted from the analysis (see Table 11).

Table 11 Focusing on Strategies 1-3

	Strategy 1	Strategy 2	Strategy 3
Weighted Social Score	0.23	0.23	0.17
Weighted Economic Score	0.10	0.17	0.16
Weighted Environmental Score	0.30	0.32	0.38
Weighted Total Score	0.63	0.73	0.72

Following this analysis, the results indicate similarly Strategy 2 as the higher scorer, but with Strategy 3 a very close second. Strategy 3 performs best in the environmental sector, while Strategy 2 performs best in the social sector and slightly better in the economic sector. Interestingly, Strategy 4 performs very well economically, mainly due to its projected revenues and reduced reliance on imports. This exercise builds on the results from Sections 5.2-5.4 and helps to better differentiate the impacts of Strategies 1-3, with Strategy 1 performing slightly worse than previously observed.

7 Discussion

7.1 Insights from the Field Work

The qualitative field work carried out in 2023 extends the findings reported in the Protocol for the Management of Sargassum for the Communities of The Sian Ka'an Biosphere Reserve and the Bonaire National Marine Park in 2021. The results largely reflect respondents' perceptions of Sargassum in Bonaire, aligning with reported disruptions to fishing and recreational water activities, as well as the economic losses caused by increased influxes. A key difference lies in perceptions of tourism impacts. In 2021, tourism was considered the most affected sector. By 2023, interviews indicate that tourism is still negatively affected by Sargassum influxes, but not to the same extent. Regarding adaptation, few respondents see it as necessary due to the distance between Sargassum-affected areas and major tourist sites. One respondent suggested diversifying tourism to reduce reliance on nature-based attractions, though perspectives on tourism development remain varied.

Another insight that surfaced is the consideration and understanding of the broader socioeconomic structures in which the impacts of Sargassum influxes occur in Bonaire. Several respondents noted that many inhabitants of Bonaire may not prioritise environmental concerns due to current social conditions. Climate justice was also raised, with some recognising that, although Bonaire contributes little to climate change, the island still faces significant challenges in managing its impacts.

7.2 Insights from the MCA

The results from the MCA highlight that there is a need to shift from the current situation of primarily landfilling organic waste on Bonaire, and that alternative waste management strategies have the potential to significantly improve social, economic and environmental impacts.

Organic waste management Strategy 2 (which uses BSFL in combination with composting and incineration) outperformed across all three alternative waste management strategies across the various MCA's that were conducted, including that of equal weighting, those under a social, economic and environmental scenario (as presented in Table 6 and 7), and also the analysis based on stakeholder weightings. The strategy performs particularly well in terms of social impacts, particularly with the availability of products of feed and composting helping to contribute to increased food security, equity and inclusion, and thereby improving the quality of life in Bonaire.

While Strategy 2 does not perform as well as Strategies 3 and 4 in terms of circularity—largely due to its smaller impact on import reduction—it performs better in other environmental criteria, such as protection of nature and pollution. This is driven by reduced emissions from landfilling and nutrient leaching, as well as the production of feed and compost, which can be used in agriculture without introducing heavy metal contamination. Strategy 1 shows similar positive social and environmental impacts as Strategy 2. However, Strategy 2 is expected to generate higher revenues and reduce import dependency more, due to the additional products it provides, such as fertiliser and feed. The use of BSFL to convert chicken manure into usable products requires relatively new technologies and specific expert knowledge, which could incur additional costs that are not fully estimated. Under current Dutch law, the use of larvae as feed is not prohibited, but an assessment of how this would apply under Bonaire law is needed.

Strategy 3 and Strategy 4 despite having potentially the highest investment costs due to the need for an anaerobic digestion plant, perform well on economic impacts overall. This is largely due to the high circularity scores that they are given, and the calculated reduced dependency on imports as fertiliser substitution (ton/yr) and diesel substitution (m³/yr). Strategy 4 also performs very well in terms of revenues but scores lower in nature protection and pollution due to heavy metals in the organic residue. Currently, dilution of such contaminated organic waste streams, such as Sargassum, is not permitted under Dutch law, so this must be considered when applying the strategy in Bonaire.

The differences among Strategies 1-3 are small in both the equal-weighting MCA. While the stakeholders attached different weights to the criteria (see section 5.4), the stakeholder-weighted MCA also shows little differences between Strategies 1-3. When the baseline strategy is removed (Table 11) and only Strategies 1-3 are compared, Strategy 1 performs less well, while Strategies 2 and 3 perform best. Strategy 1's relatively lower performance is due to reduced revenues and its smaller potential to decrease import dependency. Table 7 illustrates how different policy priorities—social, economic, or environmental—could influence strategy selection. For example, if the main policy objective is to improve economic conditions on Bonaire, particularly by reducing import dependency, Strategy 2 ranks highly, and Strategy 4 could also perform well if the environmental issue of heavy metals in its residue is addressed. Conversely, if the primary goal is to generate positive social impacts, Strategy 1 also ranks highly, providing employment opportunities through composting facilities and increasing food security via the fertiliser produced for agriculture.

The MCA illustrates that there will always have to be a trade-off based on what the policy objectives are for Bonaire. While Strategy 1 and 2 perform well socially and environmentally, Strategies 3 and 4 have the highest circular potential and the ability to reduce dependency on imports more. However, Strategies 3 and 4 do come with higher investments through increased infrastructure and specialised knowledge. All strategies involve composting part of the organic waste, and Strategies 1-3 also require treating some contaminated waste through incineration. Therefore, investment in composting and incineration infrastructure is necessary, regardless of which organic waste strategy is adopted.

7.3 Limitations and Improvements

Applying equal weighting of criteria in an MCA provides a neutral basis for strategy evaluation, yet incorporating stakeholder input is essential to capture real-world priorities. In this study, only five stakeholder responses were obtained. Future research should involve broader participatory weighting to better reflect local values, such as prioritising food security or reducing Bonaire's dependence on imports. Equal weighting remains a valuable tool for sensitivity analysis, as it allows examination of how rankings respond to the preferences of key stakeholders, including decision-makers. While current outputs are relatively insensitive to stakeholder weighting, increased participation could enhance this assessment. Further sensitivity analyses could also investigate how strategy performance varies under different weighting scenarios, thereby strengthening the robustness of the methodology and supporting evidence-based decision-making.

A key benefit of the MCA methodology is its ability to integrate both qualitative and quantitative data. However, including qualitative assessments can introduce subjectivity. Considerable effort was made to consult as many stakeholders as possible, but expanding the number of experts in future studies could further strengthen the robustness of qualitative assessments. Certain criteria—such as food security, contribution to quality of life, and carbon footprint—relied on expert judgement, which could be improved if more specific data were available for each strategy. Future work should focus on collecting additional primary data, including fieldwork, surveys, and stakeholder interviews.

The MCA provides a static snapshot of each strategy's performance based on the current or near-future conditions, and current available data and expert knowledge. The development of the four waste management strategies was based on the organic waste streams in Bonaire that were mapped by their quantity, composition and current uses. The strategies therefore might not fully account for perceived changes over time, such as quantities of organic waste (e.g. if there were to be an increase in Sargassum influx), or shifts in market conditions (e.g. price volatility in certain imported goods). While the sensitivity analysis was conducted in part by understanding how the MCA is influenced under a social, economic and environmental scenario, further analysis could be done to see how these strategies perform under different future conditions. As time progresses, new insights and developments will also mean that the amount of produce under the different scenarios will change.

Finally, normalisation sensitivity is something to consider due to the nature of the min-max normalisation for the quantitative indicators which can be sensitive to outliers, and may lead to distortion. In future analyses, a more robust normalisation method could be used such as the use of z-scores.

7.4 Other waste management options not evaluated now might be interesting

During our study, other waste management options were discussed. Due to time and resource limitations, it was not possible to fully explore these alternative options, but for the future it could be interesting to develop these options further:

1. Exporting waste to a different island with more infrastructure such as Aruba or Curacao, or other region. E.g. if the scale for digestion is too small on Bonaire, combining waste from different islands could be economically feasible.
2. Sargassum as a building material. It is known that fibres of Sargassum can be used as construction material. There are studies in Brazil and Mexico. Mexico makes bricks from Sargassum; these materials are not yet widely used.
3. Collect food waste from cruise ships and mix it with waste from Bonaire so that there is a better ratio of Sargassum to organic waste and a more constant supply of organic waste. If cruise ships pay for getting rid of the organic waste, perhaps this is economically viable.

Furthermore, the amount of Sargassum collected, and thus needed to be treated, can vary in time. Recent insights, gained after the collection of data, is that up to 5 times as much of Sargassum might have to be processed. This would require adding more processing steps (e.g. incineration) to Scenario 4.

8 Conclusions

In this report, three research questions were addressed. The first question was: **What are the current socioeconomic impacts of the Sargassum beachings?**

The fieldwork carried out in 2023 and presented in Section 4 examined Bonaire's socioeconomic impacts and management of rising Sargassum influxes. Whilst there are several socioeconomic impacts of these Sargassum beachings, a main concern voiced was the economic losses that emerge as a result of destruction to the natural environment, and the potential need for environmental conservation. Damaged mangroves and seagrass beds are mentioned, in addition to the negative impact on the fishing industry and some tourist activities such as wind-surfing. There were some discrepancies between the east and west of the island, with the eastern side experiencing the majority of the Sargassum beachings but tourists usually visiting the western side.

For the local community, the main socioeconomic impact identified was the potential health concerns associated with Sargassum decomposition and the clean-up. The unpleasant smell and unattractive appearance were also mentioned as an issue for locals.

Currently, management has shifted from manual cleanups to coordinated efforts led by STINAPA using booms and satellite tracking, though the lack of funding and capacity remain critical challenges. Community involvement is significant but there is the risk of volunteer fatigue. Despite opinions on the direct impact of Sargassum on tourism diverging between responses, it is noted that there is an indirect impact due to the damage to the natural environment. This has led to some economic losses, although there is the potential for job opportunities to clean and management the Sargassum. There is a need for further research and regional cooperation.

The next section of the report addressed the question **What are the impacts of various strategies for (co-)processing of Sargassum and organic waste?**

The co-processing of Sargassum and other organic waste streams have a positive economic, social and environmental impact when compared to the current baseline of landfilling all waste. Four organic waste management strategies were considered in this analysis, developed in parallel to this study by colleagues at WUR (Lanting et al., forthcoming) which included:

- Strategy 1: Composting & incineration
- Strategy 2: Insects, composting & incineration
- Strategy 3: Anaerobic digestion, composting & incineration
- Strategy 4: Omnivorous anaerobic digestion & composting

All four strategies have associated social impacts from the positive reduction of landfilling and the perceived opportunities from composting which takes place in all strategies. The reduction in landfilling further helps to reduce negative environmental impacts such as leaching of nutrients and heavy metals which can impact soil and water quality, in addition to the reduction in methane emissions. The increased availability of fertiliser from composting aids in increasing food security to some extent, thereby increasing the quality of life on Bonaire. While composting does provide employment opportunities across all the strategies, the work can be labour-intensive. The use of BSFL and anaerobic digestion do not provide a large number of employment opportunities due to niche and specialised knowledge which is required. All four strategies, however, do help to reduce dependency on imports which is an important policy goal in Bonaire, as fertiliser is more readily available and Strategy 2 creates additional feed and Strategies 3-4 reduce the amount of diesel required. The overall impact on nature and biodiversity is greater for all four strategies when compared to the current practice of landfilling, with the slight exception in Strategy 4 where concerns about heavy metal content in its waste residues require further investigation into what is safe and acceptable first.

It is stressed that the presented multi-criteria analysis was prepared based on data available in the first half of 2025. As time progresses, new insights into the opportunities and pitfalls of the different organic waste management strategies can call for a revision of data,

The last question addressed was the following: **How do the waste management strategies chosen in BONCIRC compare from a multi-criteria perspective?**

Based on the MCA, Strategy 2, which uses BSFL, performs slightly better than Strategy 1 (composting) and Strategy 3 (clean anaerobic digestion) in terms of social and economic impacts. Strategy 3 performs best environmentally. However, the differences are small, and overall, Strategies 1-3 perform well across all criteria, particularly when compared to the baseline landfilling strategy and Strategy 4. Results between the MCAs did not vary greatly when the weighting of the criteria by the stakeholders was included, but it is recommended that more stakeholders could be consulted with (in the waste management sector and potentially in the public) for the MCA stakeholder weighting exercise, as this will help to further include the real-world experiences of stakeholders in Bonaire.

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Appendix 1 Questionnaire on socioeconomic impacts of sargassum beachings and removal

Questionnaire Socio-Economic Impacts of Sargassum Beachings and Removal

Using this questionnaire, we want to gain insights in the socio-economic impacts of Sargassum beachings and removal on Bonaire, focusing on the impact on the local community, nature, and tourism.

Given the observation that beachings vary between years, we ask for answer for last season (2022) and the estimated average for the last five years (2018-2022).

The data collected will be used to contribute to sustainable and circular uses of Sargassum in Bonaire.

Personal Introduction

1. What is your name?
.....
2. What organisation do you represent?
.....
3. How is this organisation affected by, or involved in, Sargassum beachings and removal?
.....
.....
4. Have you noticed a change in the Sargassum beachings over the years?
(What do you think explains this and how has this changed your perception of Sargassum?)
.....
.....
5. What are your biggest concerns regarding Sargassum beachings and removal?
.....
.....

Socio-Economic Impacts of Sargassum Beachings in Bonaire

6. Who are the most impacted actors by sargassum beachings and removal? (In tourism, nature, and local community)
.....
.....
7. Who are other actors that should be (more) involved in the management of sargassum beachings and removal? (In what way?)
.....
.....

Impact on Tourism

8. What are in your view the social and economic impacts of Sargassum beachings and removal on **tourism**?
.....
.....
9. How do you think Sargassum beachings may affect the future of tourism in Bonaire?
(And how to adapt to this?)
.....
.....

Impact on Nature

10. What are in your view the social and economic impacts of Sargassum beachings and removal on **nature**? (How has sargassum beachings and removal impacted interactions with nature?)

.....
.....

Impact on Local Community

11. What are in your view the social and economic impacts of Sargassum beachings and removal on **the local community**? (How was the occurrence of sargassum beachings and removal impacted the daily lives of the local community?)

.....
.....

Other Economic Impacts

12. What are **other economic impacts** of Sargassum beachings and removal? (For whom?)

.....
.....

13. Are you aware of any (recorded) numbers (e.g., percentages or costs in US\$, etc.) that can quantify the impact of Sargassum? (On tourism, nature, or the local community?)

.....
.....

Sargassum Management

14. How is Sargassum currently removed from the beaches?

Actors:

Procedure:

Costs:

15. What do you think is the best way to manage Sargassum removal in Bonaire?

Actors:

Procedure:

Costs:

Wrapping up

16. Do you know of other studies or reports on Sargassum that we should be aware of? This can include information from other Caribbean regions.

.....

17. Are there any other relevant issues on Sargassum beachings or removal we should have discussed?

.....

- Thank you!

Appendix 2 Long-list of criteria for the Multi Criteria Analysis

Table 12 Long-list of criteria for the MCA

Category	Criterion	Description	Aspect 1	Aspect 2	Aspect 3	SUM
Social	Equity and Inclusion	Ensures fair distribution of benefits and access to resources across different social groups (e.g., gender, income, ethnicity).	1	2	-1	2
	Health and Safety	Impact on public health, safety, and well-being.	2	2	-1	3
	Community Engagement	Level of community involvement and participation in decision-making.	-1	1	-2	-2
	Cultural Heritage	Preservation or impact on cultural sites, traditions, and practices.	-1	1	-2	-2
	Social Cohesion	Strengthening or weakening of community bonds and relationships.	-1	1	-2	-2
	Quality of Life	Improvements or declines in living standards, access to services, and overall well-being.	0	2	-2	0
	Human Rights	Respect for and protection of fundamental human rights.	0	0	-2	-2
	Education and Awareness	Opportunities for education, skill development, and awareness creation	-2	2	-2	-2
	Social acceptance	The extent to which the Bonaire inhabitants and visitors value the waste management strategy.	0	0	-2	-2
	Food security	The contribution of the waste management strategy to a secure supply of safe food (import and/or local production)	1	1	0	2
	Reduce food prices	The impact of the waste management strategy on food prices	-1	2	-2	-1
Economic	Job Creation	Number and quality of jobs generated.	-2	2	0	0
	Economic Growth	Contribution to local, regional, or national economic development.	0	0	0	0
	Return on Investment (ROI)	Financial returns relative to the investment made.	2	1	2	5
	Revenue	Feasibility and competitiveness in the market.	2	1	2	5
	Income Distribution	Impact on income inequality and poverty reduction.	0	2	0	2
	Reduce import dependency	Reduction of dependence on imported products and energy	1	2	1	4
	Contribute to sustainable tourism	Support the development of sustainable tourism	0	2	0	2
	OPEX	Operational costs of the waste management	2	0	2	4
Environmental	CAPEX	Required capital expenditure for the waste management	2	0	2	4
	Circularity	Contribution to closing of nutrient cycles	2	1	2	5
	Biodiversity Conservation	Protection or enhancement of ecosystems and species diversity.	0	2	0	2
	Carbon Footprint	Greenhouse gas emissions and contribution to climate change.	2	2	2	6
	Resource Depletion	Use of renewable vs. non-renewable resources.	2	1	1	4
	Pollution	The impact of the waste management strategy on air, water, soil, and noise pollution levels.	2	2	1	5
	Water Use and Conservation	Impact on water resources and efficiency of water use	0	2	0	2
	Land Use	Changes in land use patterns and impacts on natural habitats	1	1	0	2
	Resilience to Climate Change	Ability to adapt to and mitigate climate-related risks.	0	2	0	2
	Diversion from landfill	The extent to which the waste management strategy helps to diverge waste streams from the landfill	1	2	1	4
Protection of nature	The impact of waste management strategy on quality of nature on the island	2	2	1	5	

Appendix 3 Stakeholder ranking form for MCA

BONCIRC project: Multi-Criteria Analysis questions
 Date: 15th May 2025

The aim of this question list is to select important and relevant criteria to Bonaire, particularly in the context of choosing the best waste management system for organic waste. The criteria are split between social, economic and environmental, with the following brief definitions. Comments and ideas are welcome!

Please rank from 1-10 the categories based on which you perceive to be **important**

**Ranking: 1- Very important, 2- Important, 3- Neutral
 4- Less important, 5- Not important**

Category	Criterion	Description	Ranking
Social	Food security	The extent to which the waste management can contribute to the production of food to Bonaire (direct food or via fertiliser/compost)	
	Equity and inclusion	The extent to which the waste management strategy contributes to the creation of income and opportunities for a diversity of stakeholders	
	Contribution to quality of life on Bonaire	The extent to which the waste management strategy improves quality of life on Bonaire, including but not limited to reduction of waste, improved local environment	
Economic	Investment Costs	The costs and prices to operate the waste management strategy	
	Reduced dependency on imports	The extent to which the waste management strategy reduces the need import goods/materials	
	Revenue	The extent to which the waste management strategy can be taken up by commercial, market parties (i.e. less dependent on full and/or continued government support)	
Environmental	Contribution to circular economy	The extent to which the waste management strategy contributes to materials never become waste and nature being regenerated in Bonaire	
	Carbon Footprint	The carbon footprint of the waste management strategy	
	Protection of nature	The extent to which the waste management strategy (directly or indirectly) contributes to protecting and improving the quality of nature and biodiversity on Bonaire	
	Pollution	The impact of the waste management strategy on air, water, soil, and noise pollution levels.	

Any comments?

.....

.....

.....

.....

.....

Appendix 4 Rules for inverting the ranking

Table 13 Rules for inverting the ranking

Ranking	Meaning	Inversed ranking
1	Very important	4
2	Important	3
3	Neutral	2
4	Less important	1
5	Not important	0

Appendix 5 Scores using the average weighting (five respondents)

Table 14 Scores using the average weighting (five respondents)

	Stakeholder 1					Stakeholder 2					Stakeholder 3				
	Strategy 0	Strategy 1	Strategy 2	Strategy 3	Strategy 4	Strategy 0	Strategy 1	Strategy 2	Strategy 3	Strategy 4	Strategy 0	Strategy 1	Strategy 2	Strategy 3	Strategy 4
Weighted Social Score	0.00	0.33	0.33	0.28	0.15	0.00	0.30	0.30	0.25	0.10	0.00	0.29	0.29	0.26	0.11
Weighted Economic Score	0.07	0.19	0.21	0.20	0.22	0.07	0.13	0.14	0.13	0.14	0.09	0.17	0.19	0.17	0.18
Weighted Environmental Score	0.00	0.29	0.30	0.34	0.23	0.00	0.39	0.41	0.45	0.32	0.00	0.36	0.37	0.39	0.30
Weighted Total Score	0.07	0.81	0.84	0.81	0.60	0.07	0.82	0.85	0.83	0.56	0.09	0.82	0.85	0.82	0.59

	Stakeholder 4					Stakeholder 5				
	Strategy 0	Strategy 1	Strategy 2	Strategy 3	Strategy 4	Strategy 0	Strategy 1	Strategy 2	Strategy 3	Strategy 4
Weighted Social Score	0.00	0.29	0.29	0.25	0.12	0.00	0.29	0.29	0.24	0.09
Weighted Economic Score	0.09	0.17	0.18	0.17	0.18	0.12	0.18	0.19	0.17	0.18
Weighted Environmental Score	0.00	0.36	0.37	0.41	0.29	0.00	0.35	0.36	0.39	0.27
Weighted Total Score	0.09	0.82	0.85	0.82	0.59	0.12	0.82	0.85	0.79	0.54

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REPORT 2025-119



The mission of Wageningen University & Research is "To explore the potential of nature to improve the quality of life". Under the banner Wageningen University & Research, Wageningen University and the specialised research institutes of the Wageningen Research Foundation have joined forces in contributing to finding solutions to important questions in the domain of healthy food and living environment. With its roughly 30 branches, 7,700 employees (7,000 fte), 2,500 PhD and EngD candidates, 13,100 students and over 150,000 participants to WUR's Life Long Learning, Wageningen University & Research is one of the leading organisations in its domain. The unique Wageningen approach lies in its integrated approach to issues and the collaboration between different disciplines.

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Report 2025-119

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