

## Article

# Assessing the Value of Ecosystem Services in Decentralized Sanitation Systems: A Case Study in a Vulnerable Mountain Area

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## Abstract

Decentralized waste and wastewater management systems represent a promising solution for enhancing resource efficiency and delivering ecosystem services, particularly in remote or environmentally sensitive areas. This study presents an economic valuation of ecosystem services provided by the AQUANOVA system, implemented at the Bosconero mountain hut in Northern Italy. The system integrates anaerobic digestion and phytoremediation for the treatment of organic waste and wastewater, applying circular economy principles. Using market-based, replacement cost, avoided cost, and benefit transfer methods, key ecosystem services were monetarily quantified. Results show the economic benefits generated by the system through renewable energy production, improved soil quality, reduced greenhouse gas emissions, and wastewater treatment. Depending on discount rates and climate policy scenarios, the Net Present Value (NPV) of these ecosystem services over 30 years ranges from approximately EUR 33,000 to EUR 46,000. Additionally, non-monetized benefits such as biodiversity enhancement, nutrient cycling, and cultural services further reinforce the environmental relevance of the system. These findings highlight the potential of integrating ecosystem service valuation into the assessment of decentralized waste management technologies to support evidence-based environmental policies and the transition to a circular economy.

**Keywords:** biodiversity; ecosystem services; waste and wastewater management; ecosystem services valuation; circular economy



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## 1. Introduction

The increasing loss of biodiversity is one of the most dramatic consequences of climate change and human impact on the environment. Since 2009, the rate of biodiversity loss—one of the critical “planetary boundaries” for a safe operating space for humanity—has been underestimated in the evaluation and management of business activities [1]. Biodiversity is crucial for ecosystems, and there is extensive literature emphasizing its key role in the provision of ecosystem goods and services that support human activities [2]. These services include food, raw materials, clean water, energy, climate regulation, and many others. Importantly, the economic value of these ecosystem services—underpinned by biodiversity—is immense: it has been estimated to exceed one and a half times the size of

global Gross Domestic Product GDP [3], highlighting the fundamental role of biodiversity in sustaining global extractive and productive economies. However, linear economy is responsible for more than 90% of biodiversity loss and water stress [4]. According to IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services), the main drivers of biodiversity loss can be found in 5 main causes: (i) changes in land and sea use (human actions have significantly altered 77% of land and 87% of oceans); (ii) overexploitation of species and natural resources (in 2022, humanity used nature and its resources at rates 1.75 times faster than the planet's ecosystems can regenerate); (iii) climate change (human actions have warmed the globe by more than 1 °C compared to pre-industrial levels); (iv) pollution (approximately 11 million tonnes of plastic are dumped into the world's oceans each year, affecting more than 250 animal species); (v) invasion of alien species (since 1980, cumulative records of alien species have increased by 40%, negatively affecting native species) [5,6].

In this context, it is imperative to implement transformative changes in production and consumption patterns. The circular economy can be an alternative to the dominant 'take-make-dispose' model of the linear economy and aims to address the five main drivers of biodiversity loss identified above [7]. Circular economy can be defined as a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops [8]. With the aim to change production and consumption systems by reducing the exploitation of non-renewable materials and eliminating waste and pollution, the circular economy could reduce threats to biodiversity by re-circulating products and materials to create space for biodiversity recovery and regenerating nature to support biodiversity [6]. The circular economy could be the trigger for environmental sustainability by creating awareness of how commodities can be processed and by developing an effective relationship between environmental protection/biodiversity conservation and economic development [4].

In this context, waste management plays a pivotal role, since the current linear production model lacks a comprehensive, systemic approach to waste and resource management. It is failing to integrate all stages of the production lifecycle, including product design, raw material extraction, manufacturing, consumption, and end-of-life disposal [9]. Indeed, the application of circular economy principles to waste management enhances process efficiency and minimizes natural resource consumption, thereby improving environmental performance through the reduction in greenhouse gas (GHG) emissions [10].

In the waste management framework, some technologies can provide several extremely valuable ecosystem services such as bioenergy [11], improving soil quality, and enhancing water purification [12,13], particularly if they are used in decentralized context. Decentralized waste management systems often use simpler and more affordable technologies than centralized plants [14,15]. These systems are designed to treat waste close to where it is generated, reducing the need for transportation and complex infrastructure. For example, in wastewater management, decentralized systems are typically smaller and simpler than centralized systems, making them easier and less expensive to maintain. This simplicity also allows for greater resilience to natural disasters and facilitates local reuse of treated water. Additionally, decentralized systems can be more easily adapted to the specific needs of local communities, encouraging community involvement and the creation of local resource cycles, supporting and enhancing biodiversity. Decentralized waste and wastewater systems represent a practical application of circular economy principles in support of biodiversity. By closing material and energy loops at a local scale, these systems reduce resource extraction and pollutant release, thereby mitigating two of the main drivers of biodiversity loss identified by IPBES. Their capacity to integrate energy recovery, nutrient recycling, and water treatment illustrates how circular solutions can

directly enhance ecosystem resilience while providing tangible community benefits. Typical adopted solutions in the decentralized contexts are as follows:

- local waste treatment plants: decentralized waste systems use compact and modular technologies, such as small-scale composting plants, anaerobic digestion units and mini-waste-to-energy plants, that are suitable for operation close to the waste source;
- Community-based solutions: these approaches typically encourage the direct involvement of local residents and organizations, who help sort, compost and recover resources from waste streams;
- Source separation and localized treatment: waste is sorted at the point of origin, allowing for more efficient and targeted treatment. Dedicated on-site facilities handle specific waste categories directly within the community;
- Digital tools for resource flow and matching: online platforms help connect waste producers with nearby recyclers or processors, simplifying resource exchange and supporting the development of localized circular economies.

Understanding and quantifying the ecosystem services provided by the waste management units is essential for assessing the broader benefits of the waste management and their potential role towards sustainable development.

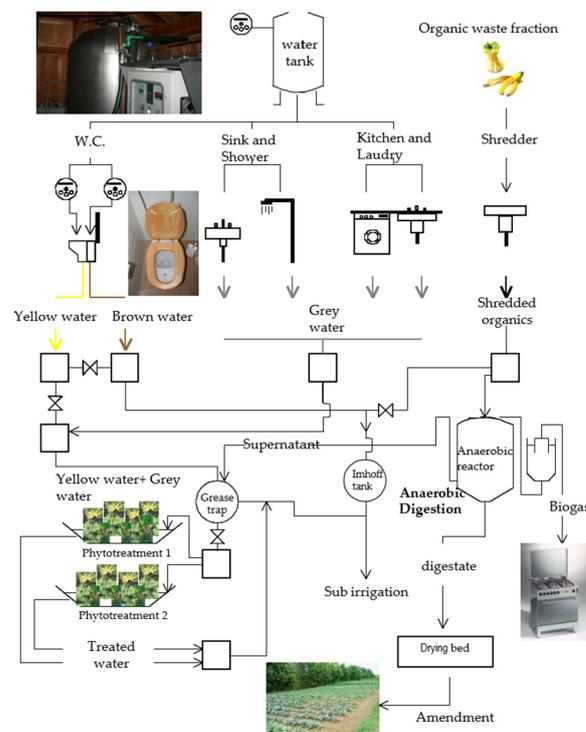
To facilitate decision-making and policy integration, the economic valuation of ecosystem services is a crucial tool. The Common International Classification of Ecosystem Services (CICES) categorizes ecosystem services into three main groups [16]: (i) provisioning services, which include the supply of resources such as food, water, raw materials, and energy; (ii) regulation and maintenance services, which involve the benefits provided by ecosystems through processes such as climate regulation, air and water purification, pollination, and soil fertility maintenance; (iii) cultural services, which encompass non-material benefits such as recreation, tourism, aesthetic enjoyment, and spiritual enrichment. Ecological life support systems form the foundation for a vast array of ecosystem services that play a crucial role in sustaining both economic activity and human well-being. These systems are integral to maintaining the health of ecosystems, which in turn provide the necessary resources and processes that support economic productivity and enhance the quality of life for people [17]. The rationale behind ecosystem services valuation is to clarify the intricate relationships between society and the environment, making it clear how human choices impact the value of ecosystem services. This approach seeks to quantify these changes in value, often in measurable units such as monetary terms, to facilitate their integration into public decision-making processes. By doing so, ecosystem valuation helps ensure that the effects of environmental decisions are explicitly understood and can be more effectively considered in policy and management strategies. Therefore, the economic valuation of ecosystem services and biodiversity highlights for both society and policymakers that these natural resources are limited and that their decline or degradation carries significant costs. By quantifying these impacts, this approach underscores the importance of biodiversity and ecosystem services, making it clear that their loss imposes tangible economic consequences on society. This information is crucial for informing decisions that aim to preserve these resources and mitigate the associated societal costs [17]. According to Dasgupta (2021) [17], economic values of ecosystem services are obtained, when possible, from data on individual behaviour observed through market transactions that directly involve the ecosystem service in question. When such data is unavailable, pricing information must be inferred from related market transactions that indirectly pertain to the good being evaluated. In cases where neither direct nor indirect price information exists for ecosystem services, hypothetical markets can be constructed to estimate their value. Therefore, there exists three different main categories for giving an economic value to ecosystem services:

*Direct market valuation* approaches use data from existing markets, reflecting current preferences and costs of individuals. Three main approaches exist: (i) market price-based, (ii) cost-based and (iii) production function-based.

*Revealed preference* techniques rely on observing individual choices in existing markets that are connected to the ecosystem service being valued. In this approach, economic agents “reveal” their preferences through the decisions they make in these markets, providing insights into the value they assign to the service. Two main approaches exist: (i) travel cost method, and (ii) hedonic pricing method.

*Stated preference* methods create a simulated market for ecosystem services by using surveys that assess how individuals respond to hypothetical scenarios, often based on policy-driven changes in the availability or quality of those services. This approach helps to estimate the demand for ecosystem services under different conditions. The three main approaches are: (i) contingent valuation method, (ii) choice modelling and (iii) group valuation.

The primary objective of this study is to conduct a comprehensive evaluation of the AQUANOVA decentralized waste management system [18] by incorporating the economic valuation of the ecosystem services it provides. This includes quantifying the financial benefits of biogas production and phytotreatment integrated in AQUANOVA (Figure 1), as well as assessing their contributions to climate change mitigation, soil quality improvement, and water purification. Additionally, the study aims to highlight the potential for decentralized waste management systems to contribute to sustainable development by reducing environmental externalities and enhancing resource efficiency. Another key objective is to explore the applicability of different economic valuation methods to ecosystem services, providing a framework that can be replicated in similar contexts. Finally, the study seeks to inform policymakers and stakeholders about the economic and environmental advantages of integrating circular economy principles into waste management strategies, ultimately supporting more sustainable decision-making processes.



**Figure 1.** Scheme of the decentralized AQUANOVA system applied at the Bosconero hut (Forno di Zoldo, BL) where wastewater and organic solid waste are treated using phytotreatment and anaerobic digestion units.

## 2. Case-Study: AQUANOVA System at the Bosconero Hut

The AQUANOVA system is a virtuous example of a decentralized wastewater management system based on the principle of source separation of domestic wastewater into distinct fractions: brown water (faecal matter), yellow water (urine), and greywater (originating from sinks and showers) (Figure 1). This separation is facilitated by the installation of experimental toilets first tested at the Department of Civil, Environmental and Architectural Engineering of the University of Padova at lab scale [18] and later applied at full scale at the Bosconero Hut, a mountain refuge located at an altitude of 1500 m in the Belluno Dolomite area, Northern Italy. These specially designed toilets play a key role in the system, as they are equipped with two separate holes and flushing mechanisms for urine and faeces. The urine flushing system uses approximately 1 litre of water per flush, while the faeces flushing system consumed 7 litres. This precise separation at the source is crucial for facilitating the distinct treatment pathways of each waste stream. The system at the Bosconero Hut consists of two main components that operate independently but in a coordinated manner: a constructed wetland, composed of two phytotreatment tanks operating in parallel, and an anaerobic digester. Yellow water characterized by high flow rates, and yellow water with elevated nutrient content (phosphorus and nitrogen), both with low organic matter content, are sent into the phytotreatment, which efficiently manages large volumes of wastewater through two subsurface horizontal flow systems.

The advantages of this system include low construction and operational costs, minimal need for specialized personnel, and seamless integration into the landscape. At the Bosconero Hut, local plant species, used in the phytotreatment, were carefully selected to ensure effective treatment but harmony with the surrounding environment [19]. Meanwhile, faeces combined with shredded kitchen waste were sent to an anaerobic digestion reactor to produce biogas. This stream, characterized by a high concentration of organic matter and a low flow rate, is particularly suited for anaerobic digestion, generating biogas composed of 50–60% methane and 40–50% carbon dioxide, suitable for bioenergy production. After digestion, the supernatant is recirculated through the phytotreatment system, while the digestate is dried and then used as a soil amendment. An Imhoff tank is designed to receive the streams in case of overflow. By efficiently managing different wastewater fractions, the AQUANOVA system optimizes nutrient recovery, enhances energy production, and reduces environmental impact. The combination of phytoremediation for yellow and greywater and anaerobic digestion for brown water and organic kitchen waste makes this a sustainable and innovative approach to wastewater management. The decentralized nature of the system ensures that it can be applied in remote or ecologically sensitive areas, requiring minimal infrastructure and maintenance while delivering significant environmental benefits.

## 3. Materials and Methods

### 3.1. Ecosystem Services of AQUANOVA Subsection

Building on the technical description of the AQUANOVA system provided in Section 2, this subsection identifies and classifies the ecosystem services generated by its main outputs, which are the relevant topic of this article: biogas production from the anaerobic digestion and treated wastewater using the phytoremediation process. Identification of the ecosystem services provided by these two outputs was carried out using the CICES as reference for their classification [16]. The potential ecosystem services related to biogas production and phytoremediation could be numerous. However, only a subset of these services was considered due to the lack of specific data required for certain economic valuation methods. In particular, approaches based on revealed and stated preferences—such as those relying on surveys, questionnaires, or market behaviour analysis—have been

excluded, as their implementation would have required extensive data collection from stakeholders, which was beyond the scope and resources of this study. Instead, priority has been given to valuation methods that can be applied using the available data. Therefore, considering data availability and previous studies such as [13] on biogas and [20] on phytoremediation, the ecosystem services considered and valued for this research are those listed in Tables 1 and 2.

**Table 1.** Ecosystem services associated with biogas production.

CICES Code	Section	Division	Group	Description	Valuation Method
1.1.3.3	Provisioning	Biomass	Reared animals for nutrition, materials or energy	Animal materials used as a source of energy or for traction	Market-based method
2.1.1.1	Regulation and Maintenance	Transformation of biochemical or physical inputs to ecosystems	Reduction in nutrient loads and mediation of waste or toxic substances of anthropogenic origin by living processes	Decomposing waste or polluting substances	Market-based method
2.3.4.2	Regulation and Maintenance	Regulation of physical, chemical, biological conditions	Regulation of soil quality	Ensuring the organic matter in our soils is maintained	Replacement cost method
2.3.6.1	Regulation and Maintenance	Regulation of physical, chemical, biological conditions	Atmospheric composition and conditions	Regulating our global climate	Avoided cost method

**Table 2.** Ecosystem services associated with phytoremediation systems.

CICES Code	Section	Division	Group	Description	Valuation Method
2.1.1.2	Regulation and Maintenance	Transformation of biochemical or physical inputs to ecosystems	Reduction in nutrient loads and mediation of wastes or toxic substances of anthropogenic origin by living processes	Filtering wastes or sequestering pollutants	Replacement cost method
2.3.6.1	Regulation and Maintenance	Regulation of physical, chemical, biological conditions	Atmospheric composition and conditions	Regulating our global climate	Benefit transfer

In the context of biogas (Table 1), a key provisioning service is the conversion of biomass from brown water and kitchen waste into energy using the anaerobic digestion process (1.1.3.3). The value of this service is estimated using a market-based approach, where the economic benefit is determined by the price of biogas in the energy market [21].

Another important service is waste decomposition and nutrient transformation (2.1.1.1), which plays a fundamental role in the circular approach of the AQUANOVA system. Through anaerobic digestion, organic waste is broken down into simpler compounds, leading to the production of digestate—a nutrient-rich byproduct that can be used as a biofertilizer. This natural recycling process reduces the environmental impact of waste disposal by decreasing the need for alternative treatments, such as landfill disposal. The economic valuation of this service is based on the avoided costs of conventional waste management solutions. Closely linked to this, is soil quality regulation (2.3.4.2), a service that highlights the role of digestate in maintaining soil health.

The application of digestate to agricultural land helps restore organic matter, improve soil structure, and enhance nutrient cycling [22]. In doing so, it reduces the reliance on synthetic fertilizers, which can be costly and have negative environmental impacts. The economic benefit of this service is estimated using the replacement cost method, comparing the value of digestate with the cost of commercial fertilizers that would otherwise be needed to achieve similar soil improvements. Finally, climate regulation through GHG emission reduction (2.3.6.1) represents one of the most significant ecosystem services provided by the AQUANOVA system. By replacing fossil fuels with biogas for energy production, the system contributes to lower carbon dioxide emissions of fossil origin. Additionally, when digestate is applied to soil, it helps store carbon, further mitigating climate change. The avoided emissions are quantified by comparing the carbon footprint of biogas-based energy with that of conventional fossil fuels. To assign an economic value to this service, the “Social Cost of Carbon (SCC)”, a widely accepted metric that reflects the monetary damage caused by each ton of CO<sub>2</sub> emitted, has been used [23].

Considering phytoremediation (Table 2), one of the most relevant services is “pollution filtration” and “nutrient load reduction” (2.1.1.2). The phytoremediation system removes pollutants, excess nutrients (such as nitrogen and phosphorus), and toxic substances from wastewater before it is discharged into the environment. This process prevents eutrophication, improves water quality, and reduces the need for conventional wastewater treatment [24]. The economic value of this service is estimated using the replacement cost method, comparing the cost of natural water treatment with the cost of conventional water treatment technologies. Another key benefit is climate regulation through carbon sequestration (2.3.6.1). Plants within the phytoremediation system absorb CO<sub>2</sub> from the atmosphere, acting as a small-scale carbon sink. While the amount of CO<sub>2</sub> captured by the constructed wetland is relatively small compared to large-scale afforestation projects, it still provides a measurable climate benefit. This service is valued using the benefit transfer method, applying existing economic estimates of carbon sequestration to the specific conditions of the AQUANOVA system.

### 3.2. Economic Valuation of Ecosystem Services

Considering the available literature on the topic and the project data availability, a mixed approach has been used. Market price-based, avoided cost and replacement cost methods have been used for the estimation of the ecosystem services related to biogas, while replacement cost and benefit transfer methods have been used for the ecosystem services related to phytoremediation. Market price-based approaches have been used for provisioning services since the commodities produced by such services are often sold on existing markets [25]. Concerning regulating services, the avoided cost methods reflecting the costs that would have incurred in the absence of ecosystem services and replacement cost methods, which estimate the costs incurred by replacing ecosystem services with artificial technologies, have been considered. Finally, the benefit transfer method has also been used to estimate the economic value of carbon sequestration by the selected phytoremediation

plants. Benefit transfer is the procedure of estimating the value of an ecosystem service by transferring an existing valuation estimate from a similar ecosystem [25].

The economic valuation of ecosystem services has been expressed on a per-unit basis, to assess the economic benefits in relation to the amount of waste processed. Specifically, the valuation is provided per kilogram of organic waste as input of the biogas plant and per cubic metre of wastewater treated by the phytoremediation system.

### 3.2.1. Economic Valuation of Ecosystem Services Related to Biogas

Provisioning service: energy production from biomass.

One of the primary ecosystem services provided by a biogas plant is the generation of bioenergy. This service can be evaluated in economic terms by quantifying the financial benefits associated with the energy produced. Specifically, the total benefit is calculated as the value of the electric energy generated. The formula used is as follows:

$$\text{Benefit of Energy production in EUR} = \text{Electric energy produced} \times \text{electric energy market price in 2023} \quad (1)$$

Regulating service: mediation of wastes of anthropogenic origin.

One of the key ecosystem services provided by the biogas plant is the treatment of organic waste, a process that is fully managed within the facility. Through anaerobic digestion, organic waste is efficiently broken down by microorganisms in an oxygen-free environment, leading to the production of biogas and digestate. This closed-loop system ensures that waste treatment occurs entirely within the plant, minimizing environmental externalities such as greenhouse gas emissions and uncontrolled waste decomposition. According to [13], the average industrial cost of treating one kilogram of organic waste is 0.11 EUR/kg. Therefore, the cost of treating one kilogram of organic waste is entirely covered by the plant's operational framework.

$$\text{Benefit of mediating 1 kg of organic waste in EUR} \quad (2)$$

Regulating service: climate Regulation.

Reduction in GHG emissions occurs through two main mechanisms: (a) the substitution of fossil fuel-based energy with biogas-derived energy, which often has a lower carbon footprint [26,27], and (b) the sequestration of carbon in the soil through the application of digestate, a carbon-rich byproduct of anaerobic digestion. To quantify the overall climate benefit, the SCC has been considered, a widely used metric that estimates the economic damage caused by emitting an additional metric ton of CO<sub>2</sub> [28]. The calculations for the two mechanisms are as follows:

(a) Emissions from Energy Substitution: by replacing fossil fuel-based energy with biogas, the system prevents significant CO<sub>2</sub> emissions. The benefit is calculated as:

$$\text{Benefit of CO}_2 \text{ emissions in EUR} = (\text{CO}_2 \text{ emissions from fossil-fuel energy per kWh} - \text{CO}_2 \text{ emissions from biogas production per kWh}) \times \text{SCC} \quad (3)$$

(b) Carbon Sequestration from Digestate Application: in addition to emission reductions, the digestate produced during anaerobic digestion serves as a carbon sink, capturing and storing carbon in the soil. This sequestration effect is also monetized using the SCC following the equation:

$$\text{Benefit of Carbon sequestration from digestate production in EUR} = \text{Quantity of Carbon from digestate per kg} \times \text{SCC} \quad (4)$$

Regulating service: regulation of soil quality

The digestate can be considered a potential source of income for many biogas plants worldwide, since it can be considered as a powerful biofertilizer [29]. Indeed, digestate is a by-product rich in nitrogen, phosphorus and potassium, which are crucial for enhancing soil quality. To quantify the economic benefits of this service, the Replacement Cost Method was considered. The percentage of  $N$ ,  $P$ ,  $K$  present in the digestate and the values for the economic value of each element were used. The formula is as follows:

$$\text{Benefit of soil quality in EUR} = \sum (N \text{ value} \times N \text{ quantity} + P \text{ value} \times P \text{ quantity} + K \text{ value} \times K \text{ quantity}) \quad (5)$$

### 3.2.2. Economic Valuation of Ecosystem Services Related to Phytoremediation

Regulating service: mediation of wastewater of anthropogenic origin.

Phytoremediation systems, such as those implemented in waste treatment plants, provide significant regulating services by enhancing water quality. To quantify the economic benefits of this service, the Replacement Cost Method [30] has been used. This approach estimates the value of the service based on the cost of alternative treatment methods. The formula used is:

$$\text{Benefit of water treatment in EUR} = \text{Treatment cost of 1 cubic metre of water} \times \text{treatment capacity of the plant} \quad (6)$$

Regulating service: climate regulation.

Phytoremediation systems also deliver regulating services by capturing atmospheric  $\text{CO}_2$  through the plants used in the remediation process. According to [31], such systems can capture approximately 12 tons  $\text{CO}_2$ /hectare/year. Given that the AQUANOVA basins have a total surface area of 80  $\text{m}^2$  (Supplementary Materials, Section S6), the annual  $\text{CO}_2$  capture is:  $\text{CO}_2 \text{ Captured} = (12 \text{ tons } \text{CO}_2/\text{hectare}/\text{year} \times 0.008) = 0.096 \text{ tons}/\text{year}$ .

$$\text{Benefit of Carbon sequestration of selected plants in EUR} = (\text{Quantity of } \text{CO}_2 \text{ captured by the plants} \times \text{SCC}) \quad (7)$$

### 3.3. Net Present Values of Ecosystem Services

Based on this information, the maximum processing capacity of the waste management system was calculated, determining the annual treatment potential of the anaerobic digester in terms of organic waste (kg/year) and for the phytoremediation plant in terms of wastewater volume ( $\text{m}^3$ /year) (Supplementary Materials, Section S4). By multiplying the maximum processing capacity with the economic benefit of the ecosystem services, it was possible to know the annual economic benefit of the plant. The aim was to calculate the Net Present Values (NPVs) of the plant, defined as the future worth of a series of cash flows (revenues, costs, or benefits) adjusted using a discount rate over a specific time period [32], using the following formula:

$$NPV = \sum_{t=0}^{t=N} \frac{Rt}{(1+r)^t}$$

where:

$R_t$  is the expected net income from the asset in period  $t$

$r$  is the discount rate

$N$  is the lifetime of the asset.

Therefore, the NPVs of the ecosystem services were calculated considering different discount rates and different scenarios. The lifetime of the asset was assumed to be 30 years.

When a discount rate is applied, it is important to distinguish between ecosystem services whose users are private economic agents and ecosystem services that contribute to collective benefits, i.e., benefits received by groups of people or society in general [32]. Concerning the ecosystem services with a private use, a discount rate of 4% was applied [33], while social discount rates of 1% and 3% were applied for the ecosystem services contributing to collective benefits [34], to reflect both long-term sustainability perspectives (1%) and more conventional public policy benchmarks (3%). Finally, according to [32], three different values have been attributed to the SCC to construct three different scenarios: (i) weak climate policy scenario: using the lowest available value for the SCC, i.e., 14.9 USD/ton of CO<sub>2</sub> (13.8 EUR/ton of CO<sub>2</sub>) [35]; (ii) moderate climate policy scenario: using an average SCC value as the one used by the US government, i.e., 51 USD/ton of CO<sub>2</sub> (47.24 EUR/ton of CO<sub>2</sub>) [35]; (iii) strong climate policy scenario: using the highest available value in the literature, equal to 417 USD/ton of CO<sub>2</sub> (386.28 EUR/ton of CO<sub>2</sub>), in [28].

#### 4. Results

Based on the methodology outlined in Section 3.2, the results of the economic valuation of ecosystem services are summarized on a per-unit basis in Table 3. Detailed calculations and underlying assumptions are provided in the Supplementary Materials (Section S8).

**Table 3.** Overview of the valuation of ecosystem services.

Ecosystem Service	Method	Formula	Result
Energy production	Market-based method	(Electric energy produced × electric energy market price EUR at 2023) (1).	0.065 EUR/kg of waste. (1).
Mediation of wastes of anthropogenic origin	Avoided cost method	Avoided cost of treating 1 kg of organic waste (2).	0.11 EUR/kg (2).
Climate regulation from biogas production	Avoided cost method	(CO <sub>2</sub> emissions from fossil-fuel energy per kWh – CO <sub>2</sub> emissions from biogas production per kWh) × SCC. (3) + (Quantity of Carbon from digestate per kg × SCC) (4).	0.014 EUR/kg of waste. (3) + 0.027 EUR/kg of waste (4) = 0.041 EUR/kg of waste (3) + (4).
Regulation of soil quality (carbon sink)	Replacement cost method	$\sum (N \text{ value} \times N \text{ quantity} + P \text{ value} \times P \text{ quantity} + K \text{ value} \times K \text{ quantity})$ (5).	0.0005 EUR/kg of waste (5).
Mediation of wastewater of anthropogenic origin	Replacement cost method	(Treatment cost of 1 cubic metre of water × treatment capacity of the plant) (6).	0.528 EUR/m <sup>3</sup> of wastewater (6).
CO <sub>2</sub> emissions savings	Benefit transfer	(Quantity of CO <sub>2</sub> captured by the plants × SCC) (7).	37.08 EUR per year (7).

#### Discounting Future Values

The results obtained by the economic analysis of discounted cash flows of ecosystem services are reported in Tables 4–6. Figure 2 shows trends and high-level comparisons. Ecosystem services that provide private benefits are discounted using a market discount rate of 4% [33], while ecosystem services that generate collective benefits are discounted using social discount rates of 1% and 3% [34]. Table 4 shows the results of the cash flows assuming a SCC value of 13.8 EUR/ton of CO<sub>2</sub> [35]. Table 5 shows the results of the cash

flows assuming a SCC value of 47.24 EUR/ton of CO<sub>2</sub> [35]. Table 6 shows the results of the cash flows assuming a SCC value of 386.28 EUR/ton of CO<sub>2</sub> [28].

**Table 4.** Net Present Values (NPVs) of the projected flows of ecosystem services generated by the plant over its operational lifespan. Weak climate policy scenario; 14.9 USD/ton of CO<sub>2</sub> (13.8 EUR/ton of CO<sub>2</sub>) [35].

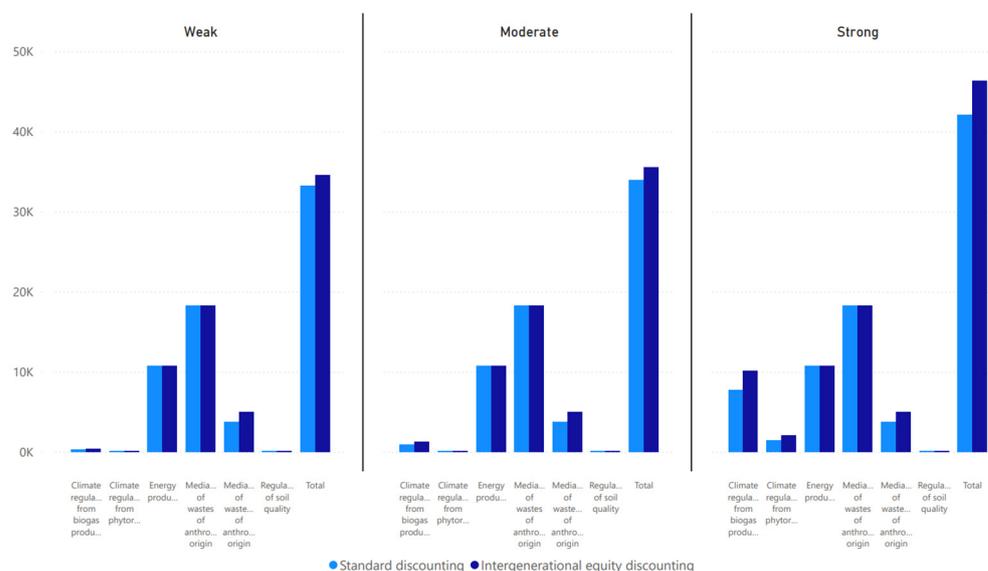
Ecosystem Service	Discount Rate			
	Private benefits: 4%	Collective benefits: 1%	Private benefits: 4%	Collective benefits: 3%
Energy production	EUR 10,797.84	-	EUR 10,797.84	-
Mediation of wastes of anthropogenic origin	EUR 18,273.36	-	EUR 18,273.36	-
Climate regulation from biogas production	-	EUR 391.58	-	EUR 297.40
Regulation of soil quality	-	EUR 123.88	-	EUR 94.08
Mediation of wastewater of anthropogenic origin	-	EUR 4992.50	-	EUR 3791.71
Climate regulation from phytoremediation	-	EUR 36.92	-	EUR 28.04
<b>Total</b>	<b>EUR 34,616.07</b>		<b>EUR 33,282.41</b>	

**Table 5.** Net Present Values (NPVs) of the projected flows of ecosystem services generated by the plant over its operational lifespan. Moderate climate policy scenario; 51 USD/ton of CO<sub>2</sub> (47.24 EUR/ton of CO<sub>2</sub>) [35].

Ecosystem Service	Discount Rate			
	Private benefits: 4%	Collective benefits: 1%	Private benefits: 4%	Collective benefits: 3%
Energy production	EUR 10,797.84	-	EUR 10,797.84	-
Mediation of wastes of anthropogenic origin	EUR 18,273.36	-	EUR 18,273.36	-
Climate regulation from biogas production	-	EUR 1241.49	-	EUR 942.89
Regulation of soil quality	-	EUR 123.88	-	EUR 94.08
Mediation of wastewater of anthropogenic origin	-	EUR 4992.50	-	EUR 3791.71
Climate regulation from phytoremediation	-	EUR 117.04	-	EUR 88.89
<b>Total</b>	<b>EUR 35,546.10</b>		<b>EUR 33,988.76</b>	

**Table 6.** Net Present Values (NPVs) of the projected flows of ecosystem services generated by the plant over its operational lifespan. Strong climate policy scenario; 417 USD/ton of CO<sub>2</sub> (386.28 EUR/ton of CO<sub>2</sub>) [28].

Ecosystem Service	Discount Rate			
	Private benefits: 4%	Collective benefits: 1%	Private benefits: 4%	Collective benefits: 3%
Energy production	EUR 10,797.84	-	EUR 10,797.84	-
Mediation of wastes of anthropogenic origin	EUR 18,273.36	-	EUR 18,273.36	-
Climate regulation from biogas production	-	EUR 10,151.64	-	EUR 7709.97
Regulation of soil quality	-	EUR 123.88	-	EUR 94.08
Mediation of wastewater of anthropogenic origin	-	EUR 4992.50	-	EUR 3791.71
Climate regulation from phytoremediation	-	EUR 2045.63	-	EUR 1447.31
<b>Total</b>	<b>EUR 46,384.84</b>		<b>EUR 42,114.26</b>	



**Figure 2.** Trends and high-level comparisons of Net Present Value of ecosystem services.

### 5. Discussion

This section discusses the results obtained from the valuation of the selected ecosystem services related to biogas production and phytoremediation and the broader implications of the findings in relation to the study’s objectives: exploring the applicability of different economic valuation methods to ecosystem services, and informing policymakers and stakeholders about the economic and environmental advantages of integrating circular economy principles into waste management strategies.

### 5.1. Valuation of Ecosystem Services

Provisioning services: clean energy supply. As it was shown previously, it is possible to generate biogas from the anaerobic digestion of organic matter and therefore obtain electric energy. In order to estimate the benefits in economic terms of clean energy provision, market-based approach has been used, since electric energy already has a price in the market. The strength of the result obtained is its tangibility since it reflects the effective value in terms of euros, having a price in the real market. On the other hand, prices change widely overtime, and they can have different values depending on the geographical location.

Regulating services: water treatment. Since most of the data on phytoremediation performance focused primarily on chemical analysis, water treatment has been included in the economic valuation using the same methodology of [30], a replacement cost method, which can be defined as an approach “which estimates the costs incurred by replacing ecosystem services with artificial technologies” [25]. Therefore, the treatment capacity of the phytoremediation system was calculated. This represents the percentage of the total wastewater volume that the system is capable of effectively treating, which is 77.67%. To estimate the economic value of this treatment capacity, this percentage was applied to the unit cost of conventional wastewater treatment, which is 0.68 EUR/m<sup>3</sup> of water [36]. This methodology allowed for the quantification of the economic benefit of phytoremediation in wastewater treatment, based on the average cost of treating one cubic metre of wastewater, which is EUR 0.528. Following the same logic of electric energy market price, it is important to report that the treatment cost of wastewater can change a lot depending on what it is included in the total cost. In this analysis, the average price for treating a cubic metre of wastewater in Italy in 2023 was considered.

Regulating services: mediation of anthropogenic waste. Another important ecosystem service that biogas production delivers is the mediation of anthropogenic waste. One of the major challenges faced by the Bosconero hut was waste management, and without the presence of anaerobic digesters to handle organic waste, they would have been forced to incur significantly higher costs. Indeed, examination of the results shows that this ecosystem service holds the highest value, which would have been even greater if the costs specific to its geographic location had been considered. However, for the purpose of this work, an average cost has been used, as it has been indicated by Tamburini et al. (2020) [13].

Regulating service, CO<sub>2</sub> emissions savings from biogas and carbon sequestration in digestate. One of the biggest advantages of producing energy from biogas in terms of ecosystem services is the fact that it is possible to produce less CO<sub>2</sub> emissions than fossil-fuel energy, which is the most common source of energy [37]. The challenge here was to value in economic terms this GHG emissions savings. The most common metric for valuing CO<sub>2</sub> emissions is undoubtedly the price of carbon credit market, since it is possible to give immediately an economic value to the CO<sub>2</sub> emissions saving [38]. However, the SCC was adopted, which is considered more suitable for the type of economic assessment conducted. As was previously explained, the SCC represents the monetary value of the damages caused to society by an additional metric ton of CO<sub>2</sub> emissions and serves as a key metric guiding climate policy [39]. Therefore, the SCC represents the damage cost of emitting CO<sub>2</sub> to society, which gives the possibility of using the avoided cost, which relates to “the costs that would have been incurred in the absence of ecosystem services” [25]. This metric is often used by governments, but the value can vary widely depending on the variables that have been taken into account. For instance, the US government’s current value is USD 51 per ton of CO<sub>2</sub> [39]. This valuation is considered particularly effective as it translates the damages from CO<sub>2</sub> emissions into economic terms, thus providing a more concrete reference for stakeholders directly impacted. On the other hand, since the estimated value of this metric depends heavily on the variables considered, the final

economic valuation of CO<sub>2</sub> emission savings can vary significantly. Following the same logic, an economic value was also assigned to the carbon contained in the digestate, which can be utilized in various ways. One valuable option to manage the digestate is to apply it as biofertilizer to the soil, because this gives the opportunity of recovering the nutrients, primarily nitrogen and phosphorus, and of attenuating the loss of organic matter suffered by soils under agricultural exploitation [40]. In this study, the digestate is returned to the soil; consequently, the amount of carbon contained in 1 kg of organic waste was calculated.

Regulating service, carbon sequestration by selected phytoremediation plants. The phytoremediation system within the AQUANOVA project plays a crucial role in carbon sequestration, contributing to climate change mitigation through CO<sub>2</sub> absorption by selected plant species. The economic valuation of this ecosystem service, estimated at EUR 37.08 per year, highlights its significance within the broader environmental benefits of the system. The carbon sequestration potential of the phytoremediation system depends on several factors, including plant species, growth rates, biomass production, and environmental conditions. According to [31], constructed wetlands with similar plant species to the ones of AQUANOVA (Supplementary Materials, Section S3) can capture approximately 12 tons of CO<sub>2</sub> per hectare per year. Given the total surface area of 80 m<sup>2</sup> in the AQUANOVA system, the annual CO<sub>2</sub> capture was estimated at 0.096 tons. This value, while lower than large-scale afforestation projects, demonstrates the additional benefits of integrating phytoremediation into wastewater treatment strategies. From an economic perspective, the valuation based on the SCC (EUR 386.28 per ton of CO<sub>2</sub>) provides a tangible measure of the climate benefits associated with the system. This valuation approach underscores the potential financial incentives for adopting decentralized wastewater treatment systems that incorporate phytoremediation. However, it is important to acknowledge the limitations of this methodology, as the actual sequestration rates may vary over time due to changes in plant physiology and ecosystem dynamics.

### 5.2. Additional Ecosystem Services of AQUANOVA

Beyond the ecosystem services that were economically valued in this study, the AQUANOVA system also provides a range of additional benefits that contribute to environmental sustainability and human well-being. While these services were not included in the monetary valuation due to data limitations or methodological constraints, their ecological and socio-economic relevance remains significant. This section provides a more detailed description of these additional ecosystem services and discusses their potential importance in the context of decentralized waste management.

Provisioning services: biomass production. The phytoremediation system contributes to biomass generation, which can have multiple applications. In the case of phytoremediation, plant growth results in biomass accumulation, which, depending on the plant species used, could be repurposed for bioenergy, compost, or other agricultural uses. However, due to the lack of precise data on the amount of biomass produced within the AQUANOVA system, this service was not included in the economic valuation. Nonetheless, its potential contribution to resource efficiency and circular economy strategies should not be overlooked.

Supporting services: Nutrient cycling (*N* and *P*) and habitat formation. According to [20,41], one of the key ecological benefits of phytoremediation is its role in nutrient cycling, particularly in the retention and exchange of *n* and *p*. These nutrients are essential for soil fertility and agricultural productivity, and their natural recycling reduces reliance on synthetic fertilizers, contributing to more sustainable agricultural practices. While data on the amount of *n* and *p* captured by the system were available, their economic valuation posed a challenge due to variability over time. The efficiency of nutrient uptake by plants

is influenced by multiple environmental factors [42], making it difficult to assign a stable monetary value to this service. Another important supporting service is habitat formation. Constructed wetlands, such as the one implemented in AQUANOVA, create suitable conditions for various plant and animal species, enhancing local biodiversity and contributing to ecosystem resilience. Several studies have attempted to monetize this service by estimating the economic value of wetlands in different geographical contexts [43–45]. However, due to the significant ecological and climatic differences between these case studies and the AQUANOVA site, transferring those values to this context would be methodologically inappropriate. While habitat formation was not monetized in this study, it remains a crucial ecosystem service that should be considered in the broader assessment of AQUANOVA's environmental impact.

**Cultural services:** Biodiversity, educational and aesthetical services. Finally, considering the cultural services, it is possible to identify many ecosystem services related to phytoremediation and biogas production. Cultural services refer to the intangible benefits that nature provides to humans meaning by the interaction between humans and ecosystems [46]. According to [20], it is possible to identify three different types of ecosystem services related to phytoremediation: (i) biodiversity, meaning that constructed wetland, such as phytoremediation in AQUANOVA system, can enhance biodiversity at various levels by providing suitable breeding habitats for various animal species [47]; (ii) educational services, meaning that such system could be exploited as a source for educating people which are benefiting phytoremediation; (iii) aesthetics services, meaning that the phytoremediation plant could be seen as a set of benefits including physical, mental, and emotional well-being benefits [48]. The economic valuation of cultural services often relies on revealed or stated preference methods (e.g., willingness to pay surveys, contingent valuation), which require direct input from beneficiaries. Due to the lack of qualitative data regarding local perceptions and preferences, these services were not included in this monetary analysis. However, their socio-environmental relevance suggests that future research should explore ways to integrate cultural services into holistic assessments of decentralized waste management projects.

### *5.3. Discussion of the Net Present Values*

The economic analysis of the Net Present Values of ecosystem services reveals that the total economic benefits of the system vary significantly depending on which parameters and assumptions are implemented, in particular the discount rate and the SCC. Depending on the assumptions made in the different scenarios, total benefits can vary from EUR 46,384.84 in 30 years (highest value of SCC and lowest discount rate) to EUR 33,282.41 (lowest value of SCC and highest discount rate). This decline clearly highlights the impact of discounting in long-term infrastructure investments, particularly for sustainability projects where future benefits may be undervalued. Policymakers should carefully consider the implications of higher discount rates, as they may disincentivize investments in decentralized waste management systems despite their long-term environmental and economic advantages. It is important to note that the actual implementation costs of the AQUANOVA project were not reported in this study. The project was developed in a high-altitude mountainous region, where construction and operational costs are considerably higher than in standard settings. These increased costs arise from logistical challenges, transportation expenses, and the need for specialized infrastructure. As such, while the cost–benefit analysis demonstrates the economic viability of the system, its replicability in less expensive contexts would likely yield even greater financial feasibility. Future assessments should explore site-specific cost variations to provide more tailored policy recommendations.

## 6. Conclusions

This study highlights the environmental and economic value of decentralized waste management systems based on circular economy principles, using the AQUANOVA project as a case study. Through a mixed-method approach to ecosystem service valuation, key benefits such as renewable energy generation, waste treatment, climate regulation, water purification, and soil improvement were quantified. Assuming a 30-year lifespan for the project, the NPVs of all future ecosystem service flows provided by AQUANOVA ranges from approximately EUR 33,000 to EUR 46,000. However, it is important to acknowledge that should the fundamental assumptions underlying this study (i.e., discount rates, climate policy scenarios, lifespan of the plant, etc.) be subject to change, the results may deviate significantly from the estimated values. These figures emphasize the importance of accounting for both private and societal benefits in sustainability-related infrastructure planning. Beyond the monetized services, the AQUANOVA system delivers additional non-market benefits such as biodiversity support, nutrient cycling, habitat creation, and educational and aesthetic value, which further strengthen its role as a nature-based solution for sustainable waste management in remote or ecologically sensitive areas. One of the main strengths of this research lies in the integration of multiple economic valuation approaches—including market-based methods, replacement cost techniques, and the SCC—providing a comprehensive and replicable framework for assessing the value of ecosystem services in decentralized waste management systems. By translating ecological benefits into economic terms, this approach enhances the visibility of ecosystem services in decision-making processes and provides concrete arguments to support the implementation of circular economy initiatives. However, the methodology also presents some limitations. Market-based approaches are well-suited for services with clear market prices, such as energy, but the economic valuation of non-market benefits like biodiversity or cultural services remains complex and was excluded from the monetary analysis due to methodological and data constraints. Furthermore, the SCC, while useful for quantifying climate-related benefits, is sensitive to policy assumptions and can vary considerably across different studies and contexts, which may affect the overall economic estimations. The originality of this study lies in being the first documented application of the AQUANOVA system in a high-altitude alpine context and in explicitly linking decentralized sanitation with the economic valuation of ecosystem services. The study also acknowledges that site-specific factors, such as waste composition, energy prices, and regulatory frameworks, can influence the replicability of the results. Moreover, construction and operational costs in high-altitude areas like the Bosconero hut are significantly higher than in standard settings, which should be considered when evaluating the system's economic viability in other locations. Despite these limitations, the results suggest that decentralized waste management systems, particularly those integrating phytoremediation and anaerobic digestion, can play a significant role in achieving climate goals, improving resource efficiency, and enhancing ecosystem services. Policymakers are encouraged to support these technologies by introducing targeted incentives, such as subsidies or feed-in tariffs, and by integrating ecosystem service valuation into environmental impact assessments. In particular, further efforts are needed to standardize methodologies for assessing carbon sequestration and to develop reliable approaches for the monetary valuation of non-market ecosystem services. Future studies should focus on quantifying non-valued ecosystem services, such as biodiversity and cultural benefits, and on performing a full cost-benefit analysis that explicitly includes the higher installation and operational costs typical of mountainous areas. This would allow for a more accurate assessment of the overall economic viability and replicability of decentralized sanitation systems. Overall, this study provides a robust foundation for future research and policy development aimed at promoting decentralized,

multifunctional, and nature-based waste management solutions as a concrete contribution to the circular economy and biodiversity conservation.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su17188186/s1>, Table S1: Energy produced in kWh per kg of waste for the years 2009; 2011; 2012; 2013; 2016; 2017. The data has been collected on the field. Table S2: Data collected in Summer 2007 of quantity of wastewater entering in the plant ( $Q_{in}$ ) and quantity of water treated ( $Q_{out}$ ). Refs. [49–51] are cited in Supplementary Materials.

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