Supplementary Materials

Section S1. Energy production: To calculate the benefit of energy production in EUR deriving from the production of biogas, we calculated how much electric energy it is possible to generate from 1 kg of organic waste that enters the anaerobic digester. In order to do that, we used data from a Master's thesis entitled *"Energy recovery from decentralized wastewater networks: the case study of Bosconero hut"* written in 2018. We used data from the following years: 2009; 2011; 2012; 2013; 2016; 2017. In the following table are reported (i) the year considered; (ii) the electric energy produced in kwh; (iii) the total amount of organic waste in kg; (iv) the ratio between electric energy and organic waste.

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.

Year	Electric energy in kwh	Organic waste in kg	Energy per kg of waste
2009	36,5	186,54	0,196 kwh x kg
2011	4,83	117	0,041 kwh x kg
2012	36,17	201,08	0,18 kwh x kg
2013	3,67	191,4	0,02 kwh x kg
2016	10,84	22,58	0,49 kwh x kg
2017	15	182,02	0,082 kwh x kg

Therefore, it is possible to calculate the average quantity of energy produced per kg of waste, which is **0.17 kwh per kg of waste.**

Section S2. Water supply: To calculate the benefit of water supply deriving from the phytoremediation plant, we calculated the treatment capacity of the plant, which is the percentage of wastewater that is treated. The treatment capacity was calculated by dividing the amount of wastewater entering into the phytoremediation with the amount of water that goes out the plant. We used data from another Master's thesis entitled *"Analisi delle efficienze di rimozione di un impianto di fitodepurazione a flusso sub-superficiale" (Analysis of removal efficiencies of a sub-surface flow phytoremediation plant)* written in 2008. We decided to use older data because the treatment capacity was better at the beginning. In the following table are reported (i) time of data collection in the summer 2007 (day by day); (ii) quantity of wastewater entering in the plant (Q_{in}); (iii) quantity of water treated (Q_{out}).

Table S2: Data collected in Summer 2007 of quantity of wastewater entering in the plant (Q_{in}) and quantity of water treated (Q_{out}).

Time	Q_{in} (m^3)	Q_{out} (m^3)
t-1	0,417	0,075
t-2	0,392	0,665
t-3	0,355	0,369
t-4	0,309	0,369
t-5	0,392	0,369
t-6	1,025	0,640
t-7	N/D	N/D
t-8	0,800	0,178
t-9	0,822	0,839
Total	**4,512**	**3,504**

We decided to not include t-7 because it rained in that day. Therefore, it is possible to calculate the treatment capacity by dividing Q_{out} with Q_{in}. The result is 0.77659, giving **77.659%.**

Section S3. Selected plant species: The names of the selected species are as follows:

- Aconitum Lycoctonum;
- Adenostile Alpina;
- Epilobium Agustifolium;
- Mentha, Myrris Odorata;
- Rumex Bonus Enricus;
- Senecio Cordatum.

Section S4. Maximum capacity of the plant: For the purpose of this study, it was decided to consider the maximum capacity of the plant in performing cost–benefit analysis. Therefore, the idea was to calculate the maximum amount of organic waste that the anaerobic digester is able to treat per year and the maximum amount of wastewater that the phytoremediation plant is able to treat per year. Considering that the anaerobic digestor has a volume of 1,7 m^3 and a retention time of 10 days, it was calculated that it can treat 0.17 m^3 per day. In order to understand how many kilograms of organic solid waste the plant is able to treat per year, we performed the following calculations: considering that one person produces 0.344 kg of organic waste and assuming that the plant can host a maximum of 30 people per day, we found the maximum amount of kilograms of organic waste that enters the anaerobic digestor: 0.344*30= 10.32 kg per day, or 0.01032 m^3. Knowing that the maximum volume of the digester is 0.17 m^3 per day, we know that the maximum volume of brown water that can enter the digester is 0.159 m^3 per day (0.17 - 0.01032). Therefore, we multiplied 0.159 m^3 by 365 days to get 58.4m^3 of brown water per year, which is 58400 litres of brown water. Considering that only 10% of that brown water is organic solid waste, the total amount of organic solid waste coming from brown water that enters in the digester is **5840 kg per year.** Therefore, adding the organic solid waste coming from daily human consumption (10.32 kg*363= **3766.8 kg per year**) and the organic solid waste coming from brown water, we have: 5840kg+3766.8= **9606.8kg per year.**

The phytoremediation plant is able to treat 1 m^3 of wastewater per day. Therefore, it can treat 365 m^3 of wastewater per year (1*365= **365 m^3 of wastewater per year**).

Section S5. CO2 emissions savings from energy production: We know that we can produce on average 0.17 kwh of electric energy per kg of waste entering the anaerobic digester. We can convert this amount of energy in MJ by multiplying for 3.6. Therefore, we know that for every kg of waste, we produce 0.612 MJ (0.17*3.6). According to Tamburini et. al., 2020, we also know that for every 1 MJ of electric energy from fossil fuel, we produce 83.8g of CO2, while from biogas, we produce 25g of CO2. Assuming that we produce 0.612 MJ of energy, we know that we emit 51.3056g of CO2 for fossil fuel (83.8*0.612) and 15.3g of CO2 for biogas (25* 0,612). **The avoided emissions are as follows: 51.3056-15.3= 36.0056 g of CO2 per 1 kg of waste.**

Section S6. CO2 emissions savings from the phytoremediation plant: We know that Aquanova has two pools of 40 m2 each; 80 m2 in total. According to De Klein and van der Werf (2014), we know that a wetland with a surface of 1 hectare with similar plant species is able to sequestrate 12 tons of CO2 every year. Therefore, we made a simple proportion: 12:10000=x:80; **result: 0.096 tons of CO2 every year.**

Section S7. Soil quality (N,P,K digestate). We know that we can produce 70g of digestate per 1 kg of waste that enters the AD (data taken from the field). Therefore, we produce 1 kg of digestate for every 14.3 kg of waste. According to Guan et. al., 2024, we know the percentage of NPK in 1 kg of digestate:

N: 3-6 g in 1 kg= 0.003-0.006 kg

P: 0.11-0.33 g in 1 kg= 0.00011-0.00033 kg

K: 1.9-3.2 g in 1 kg= 0.0019-0.0032 kg

According to Czekala et. al., 2020, the value in EUR per every component is as follows (the value is an assumption based on the fact that you do not sell the product in the market, but you spread the digestate in the soil):

N= 0,7 EUR per kg; **P**= 1,06 EUR per kg; **K**= 0,55 EUR per kg

Therefore, the ES benefit in terms of kg of digestate is as follows:

N= (0,0021-0,0042 EUR) per kg of digestate.

P= (0,00012-0,00035 EUR) per kg of digestate.

K= (0,0011-0,0017 EUR) per kg of digestate.

But, since we know that to produce 1 kg of digestate, we need 14,3 kg of waste, it is possible to know the ES benefit in terms of kg of waste by dividing by 14,3:

N= (0,00015-0,0003 EUR) per kg of waste.

P= (0,000008-0,00003 EUR) per kg of waste.

K= (0,00007-0,00013 EUR) per kg of waste.

Sum= 0,0003-0,0005 EUR per kg of waste.

Section S8: Full methodology of the calculations and assumptions made for the economic valuation of ecosystem services.

4.1 Ecosystem services of biogas

4.1.1 Provisioning service: energy production from biomass (1.1.3.3).

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:

Benefit of energy production in EUR = Electric energy produced * electric energy market price in 2023 (S1)

The analysis assumes that the electric energy output from 1 kg of waste is 0.17 kWh (Supplementary Materials, Section S1), with the market price of electric energy set at 0.38 EUR/kWh [1]. Based on these parameters, the calculation is:

Benefit of energy production in EUR = (0.17kWh * 0.38 EUR/kWh) = 0.065 EUR/kg of waste

4.1.2 Regulating service: mediation of wastes of anthropogenic origin (2.1.1.1).

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 [2], 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.

Benefit of mediating 1 kg of organic waste in EUR = Avoided cost of treating 1 kg of organic waste = 0.11 EUR/kg (S2)

4.1.3 Regulating Service: climate Regulation (2.3.6.1).

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 [3,4], 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_2 [5]. 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_2 emissions. The benefit is calculated as:

Benefit of CO_2 emissions in EUR = (CO_2 emissions from fossil-fuel energy per kWh - CO_2 emissions from biogas production per kWh) * SCC (S3)

Where the CO_2 emissions from fossil-fuel energy are 51.286 g CO_2 per kWh [13]; the CO_2 emissions from biogas production are 15.3 g CO_2 per kWh [2]; and the SCC is 386.28 EUR/ton of CO_2 (417 USD/ton of CO_2) [5]; therefore:

Benefit of CO_2 emissions in EUR= (51.286 g CO_2 per kWh – 15.3 g CO_2 per kWh) * 386.28 EUR/ton of CO_2 = 0.014 EUR/kg of waste

(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:

Benefit of carbon sequestration from digestate production in EUR = Quantity of carbon from digestate per Kg * SCC (S4)

The digestate is assumed to contain 70 g CO_2/kg [6] and the SCC is 386.28 EUR/ton of CO_2. Therefore:

Benefit of carbon sequestration from digestate production in EUR = (70g CO_2/kg * 386.28€/ton of CO_2) = 0.027 EUR/kg of waste

Total Climate Regulation Benefit: by combining both mechanisms—the reduction in CO_2 emissions from energy substitution (0.014 EUR/kg of waste) and carbon sequestration through digestate application (0.027 EUR/kg of waste)—the total economic benefit of climate regulation provided by the biogas system amounts to 0.041 EUR/kg of waste.

4.1.4 Regulating service: regulation of soil quality (2.3.4.2).

The digestate can be considered a potential source of income for many biogas plants worldwide, since it can be considered as a powerful biofertilizer [6]. Indeed, digestate is a by-product rich of 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, and K present in the digestate and the values for the economic value of each element were used. The formula is as follows:

Benefit of soil quality in EUR = ∑ (N value * N quantity + P value * P quantity + K value * K quantity) (S5)

Where N value is 0.7 EUR/kg; P value is 1.06 EUR/kg; K value is 0.55 EUR/kg [7]; N quantity is 0.42 g/kg of waste; P quantity is 0.03 g/kg of waste; K quantity is 0.13 g/kg of waste [8] (Supplementary Materials, Section S7). Therefore:

Benefit of soil quality in EUR = ∑ (0.7 EUR/kg * 0.42 g/kg + 1.06 EUR/kg * 0.03 g/kg + 0.55 EUR/kg * 0.13 g/kg) = 0.0005 EUR/kg of waste

4.2 Ecosystem services of phytoremediation

4.2.1 Regulating service: mediation of wastewater of anthropogenic origin (2.1.1.2).

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 [9] was used. This approach estimates the value of the service based on the cost of alternative treatment methods. The formula used is:

Benefit of water treatment in EUR = Treatment cost of 1 cubic metre of water * treatment capacity of the plant (S6)

The cost of treating one cubic meter of water is 0.68 EUR/m^3 [1], and the plant's treatment capacity is 77.67% (Supplementary Materials, Section S2). Thus:

Benefit of water treatment in EUR = (0.68 EUR/m^3 of water * 0.7767) = 0.528 EUR/m^3 of wastewater

4.2.2 Regulating service: climate regulation (2.3.6.1).

Phytoremediation systems also deliver regulating services by capturing atmospheric CO_2 through the plants used in the remediation process. According to [10], such systems can capture approximately 12 tons CO_2/hectare/year. Given that the AQUANOVA basins have a total surface area of 80 m^2 (Supplementary Materials, Section S6), the annual CO_2 capture is: CO_2 Captured = (12 tons CO_2/hectare/year * 0.008) = 0.096 tons/year.

Benefit of carbon sequestration of selected plants in EUR = (Quantity of CO_2 captured by the plants * SCC) = 0.096 tons of CO_2 * 386.28 EUR/ton of CO_2= EUR 37.08 per year (S7)

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