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Thermodynamic and Economic Simulation of an Organic Rankine Cycle for the Utilization of Combustion Gas Produced in Small Landfills in Antioquia, Colombia

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Abstract: This study presents a simulation of an organic Rankine cycle (ORC) for the utilization of combustion gas produced in small landfills in Antioquia, Colombia, with a focus on the municipality of Angostura. This municipality has been chosen as the focus of this study due to its growing population and industrial and tourism development, bringing with them the need for sustainable waste and energy management solutions. The proposed ORC system includes two evaporators, two turbines, a condenser, a pump, and a generator, similar to successful systems reported in the literature. A sensitivity analysis was performed to investigate the impact of pressure, temperature, and mass flow on the system's net power output and thermodynamic efficiency. The results showed that the system reached a net power output of 64.33 kW with an overall power plant efficiency of 13.03% and an investment cost of 192, 340 USD based on a reference cost of 2990 USD/kW. The study also found that the system's use in Angostura is economically feasible, with a net present value of 31, 208 USD over a 10-year investment study. The sensitivity analysis revealed that temperature and pressure have direct effects on the system's performance and economic viability. The municipality's geomorphological characteristics were found to reduce the risk of groundwater contamination, while surface waters may still be vulnerable to contamination from leachates. Overall, this study highlights the feasibility and potential benefits of utilizing an ORC system, in which the combustion heat from methane gas produced in small landfills in Antioquia, Colombia, is harnessed for energy production.

Keywords: environment; landfill; methane gas; organic Rankine cycle; South America

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1. Introduction

As the population continues to grow, and human development increases exponentially, several questions arise about the increase in the amount of waste generated by anthropogenic activities [1]. This waste is typically disposed of in landfills or incinerators, which have significant drawbacks. These methods can lead to potential contamination from leachate and gases, which can mobilize into the atmosphere and into surface and groundwater sources, as well as into nearby low-lying areas and surface water bodies during the rainy season, potentially impacting the local environment [2–4]. These issues, along with increasing energy demand and climate change, are major concerns for a sustainable future [5].

In recent years, the scientific community has focused its attention on managing energy sources that prioritize security of supply, environmental friendliness, economic affordability, and societal acceptance [6]. These concerns are where methane gas, a potent byproduct of waste disposal, plays a crucial role. Methane gas is 25 times more effective at trapping heat in the atmosphere than CO_2, making it a significant contributor to global warming [7]. However, it also carries high energy potential and can be harnessed to generate electricity. Conventional cogeneration systems, such as Rankine steam cycles, often exploit this potential, although these systems require high temperatures and substantial amounts of thermal energy, making them unsuitable for small landfills with lower methane production [8].

The use of organic Rankine cycles (ORCs) presents an alternative solution, using organic fluids, such as R134a and R245fa, as the working fluid. These fluids have lower boiling points and smaller heat capacities compared to water, enabling them to efficiently convert low-grade thermal energy into electricity [9]. This ability is particularly useful for small landfills where methane gas generated is limited, and the gas temperature is not high enough to drive a traditional Rankine cycle [9]. In an ORC, the lower boiling point of the organic fluid enables the cycle to operate at lower temperatures and with smaller heat exchangers.

As a result, ORCs can be a more cost-effective option for small landfills compared to traditional Rankine cycles. The lower operating temperature and pressure in ORC systems reduce wear on the components, leading to lower maintenance costs [9]. Additionally, the higher efficiency of ORCs results in a higher return on investment, as more electricity can be generated per unit of methane gas [9]. A study conducted by Aracil et al. [10] evaluated and compared the economic and environmental impacts of several waste-to-energy schemes for generating electricity from municipal solid waste refuse with landfill disposal. The study included both incineration and gasification alternatives. It found that both incineration and gasification improve landfill disposal and contribute favorably to greenhouse gas reduction. However, the three gasification options analyzed yielded lower greenhouse gas emissions than incineration. The study concluded that, in landfill-dominated countries, ORCs are a better short-term option due to their higher technical reliability and the currently low gate fee available in these countries. Anastasovski et al. [11] pointed out the potential benefits of incorporating ORCs technologies at landfills. This approach can significantly reduce negative impacts associated with landfill discharges and emissions, including resource recovery from waste and decreasing the amount of waste requiring disposal. Additionally, it helps to minimize the need for new landfills, thus reducing the overall environmental impact of waste management [12]. A study carried out by Sununta et al. [13] evaluated the life cycle greenhouse gas emissions from the implementation of an ORC as a waste-to-energy technology using refuse-derived fuel (RDF) in Thailand. The study found that the RDF hybrid ORC system demonstrated itself to be an environmentally friendly option, reducing greenhouse gas emissions by 51.47% compared to an open dump and 34.31% compared to a landfill. This study showed the potential for RDF hybrid ORC systems to be considered as sources of power generation in future power planning in Thailand. Similarly, Quebedo-Rodrigez et al. [14] proposed a smart hybrid power plant that combines a waste-fired CHP (combined heat and power) plant with a small-scale organic Rankine cycle, aiming to maximize the share of electricity production cost-effectively. The study examined the potential of exergy utilization of the hot flue gas of the waste-fired CHP unit to increase the potential of the organic Rankine cycle and improve the net power output of the hybrid cycle. The authors demonstrated that the combined plant's net exergy and energy efficiency were enhanced compared to the plant's primary configuration, in which both the main CHP cycle and the organic Rankine cycle were operated at nominal load. Furthermore, the exergy utilization led to a 10% decrease in the payback period of the parallelization. This study emphasized the importance of ORCs in enhancing the power output of hybrid power plants, as well as increasing their energy efficiency. The ORC system proved to be advantageous in terms of energy and economic efficiency, with a notable increase in the net power output of the hybrid cycle and a reduction in the payback period of the parallelization project.

ORC technology has also been demonstrated to have potential in various industries. For example, ORC systems have been effectively utilized to recover waste heat from the flue gases of large ships [15]. The technology has also been studied for recovering waste heat from automotive engines, with a system capable of producing up to 28 kW of electricity from the waste heat produced by large truck engines [16]. Moreover, ORC systems driven by the incineration of municipal waste in landfills have also been used successfully, with installations generating up to 1100 kW by combining steam turbines and ORC systems to collect waste heat [14]. These examples demonstrate the versatility and potential of ORC technology in generating electricity from diverse low-grade thermal energy sources, enabling its application across various sectors in which traditional systems may not be suitable.

In this context, our research focuses on the potential of ORC technology in the department of Antioquia, Colombia. The region is home to approximately 120 landfills receiving waste from urban centers, with only a few harnessing the energy potential of methane through cogeneration systems [17,18]. This process leads to high greenhouse gas emissions, which are a concern considering Colombia's commitment to reducing emissions by 20% by 2030 [19]. The use of waste to produce energy using an ORC system becomes particularly interesting in Antioquia, as several municipalities in the department are undergoing significant population growth, as well as industrial and tourism development, creating demand for sustainable waste and energy management solutions. In this study, we focus on the municipality of Angostura as a representative case of this trend in Antioquia.

In view of this case, the goal of this research is to evaluate the use of ORC systems for energy production from waste, particularly in the small landfills of the rapidly growing municipality of Angostura. Our objectives are: (1) to present a simulation of an ORC system for the utilization of combustion gas in the small landfills of Angostura; (2) to perform a sensitivity analysis examining the influences of pressure, temperature, and mass flow on the net power output and thermodynamic efficiency of the system; (3) to study the economic viability of this project using the net present value (NPV) method; and (4) to qualitatively assess the vulnerability of groundwater and surface water ecosystems to pollution due to their interactions with the landfill. The economic viability of the project is studied considering the project's investment cost, along with the earnings from the energy produced and the energy consumption costs, as well as maintenance and operations, to calculate the annual cash flow over a 10-year period. Additionally, a qualitative comparison is performed to assess the vulnerability of groundwater and surface water ecosystems to pollution in relation to their interactions with the landfill. The evaluation considers factors such as hydrological distribution and the overlap of hydrological networks, which are influenced by the department's climatic and geomorphological conditions. In evaluating groundwater susceptibility, we considered the recharge potential of the aquifers. Geomorphological conditions and human activities significantly influence this potential.

We believe that the results of our study can serve as a model for other areas in the department and provide insights for sustainable waste and energy management solutions in regions experiencing significant population growth and development.

2. Case Study

Antioquia is one of the 32 departments of Colombia, located in the central–western region of the country. It is divided into nine subregions of political management with territorial jurisdiction, which are responsible for facilitating the administration of each sector [20]. The department comprises 125 municipalities and is recognized for its important role in national economic development, particularly in the mining, agricultural, and trade sectors [21]. Moreover, Antioquia plays a prominent role in the tourism industry, attracting visitors from all over the world with its diverse range of natural and cultural attractions [22]. Most of the energy production in Antioquia relies heavily on hydroelectric sources, followed by thermal sources, such as coal and natural gas. However, there is also growing adoption of renewable energy sources, including solar and wind, within the department [23]. The energy production characterization of Antioquia is depicted in Figure 1.

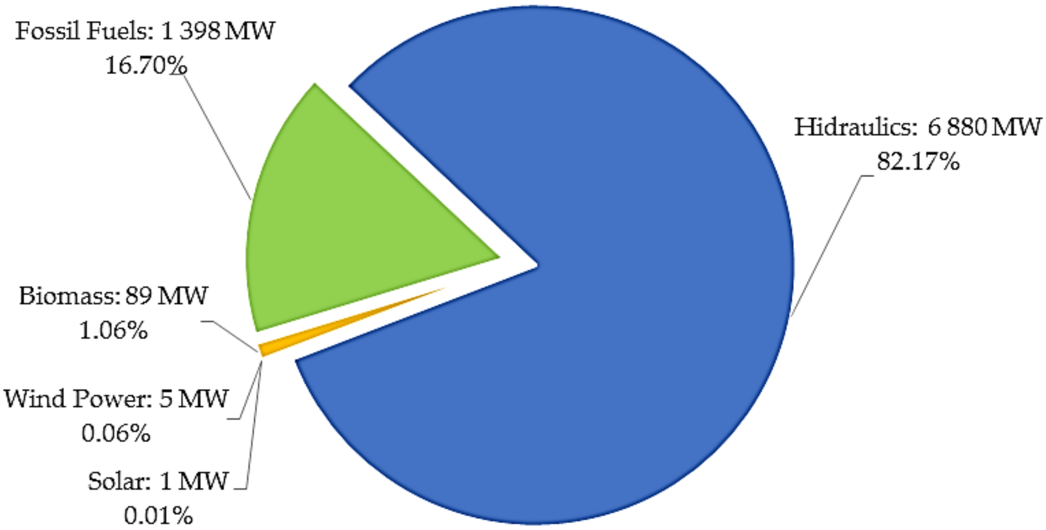

Figure 1. Energy production in the department of Antioquia.

The Hidroituango hydroelectric project's construction and operation in Antioquia have spotlighted the issues inherent to large-scale energy production [24]. Initiated in 2009, the project met several challenges, including a partial tunnel collapse and a 2018 landslide that necessitated a temporary evacuation of neighboring towns. This series of setbacks delayed the project [25]. As a result, the region has pivoted toward distributed energy generation, launching numerous small-scale power plants. These plants exploit locally accessible resources, such as solar and wind power, and use waste [26].

One of the most promising options for waste utilization is the production of combustible gases from landfills [27]. Considering these issues, this article aims to analyze the potential for utilizing waste in distributed energy generation in the department of Antioquia, with a focus on the use of gases derived from landfills.

Over the past 17 years, the department of Antioquia has implemented various waste management strategies, including the use of landfills, recycling treatment plants, and incineration facilities. In 2021, the departmental government introduced the "Zero Garbage" program as part of the Departmental Development Plan, with a focus on integrated solid waste management [28]. This initiative has led to actions aimed at improving the provision of sanitation services through the collection, transportation, final disposal, transformation, and utilization of waste [28]. To date, the department has achieved the diversion of 35 tons of solid waste from landfills, with plans to divert an additional 10 tons [29]. According to the Integrated Solid Waste Management Plan for the Antioquia region, by the beginning of 2023, the waste management distribution will be as follows: 1784.41 tons (96.01%) will be sent to landfills, 36,800 tons (1.98%) to open dumps, 31,410 tons (1.69%) to contingency cells, and 4089 tons (0.22%) to transitory cells, and 1859 tons (0.1%) will undergo energetic valorization in treatment plants and/or local incinerators within the department [30]. Figure 2 shows the per capita solid waste generation in the department of Antioquia from 2006 to 2023.

The municipality of Angostura, located in the northern sub-region of the department of Antioquia, was chosen as the focal point of this study for several reasons. First, the municipality is experiencing significant growth in tourism, population, and industry, bringing the need for sustainable waste and energy management solutions [31]. Second, Angostura has a small landfill that provides a source of methane gas, which can be combusted to generate heat for energy production using an ORC system. Additionally, the northern Antioquia sub-region demonstrates considerable potential for utilizing renewable energy sources, such as solar power, which can complement the energy produced by the ORC system. Furthermore, the development of sustainable energy solutions in this municipality could serve as a model for other areas in the department of Antioquia and beyond, providing a sustainable approach to address the waste management and energy production challenges.

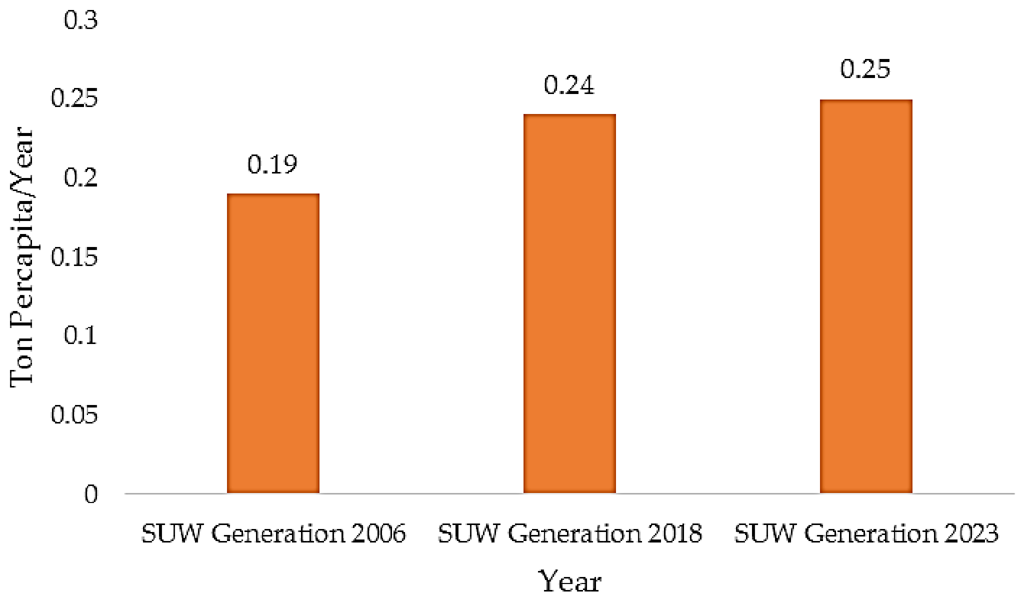

Figure 2. Per capita generation of waste in Antioquia.

3. Materials and Methods

3.1. Thermodynamic Modelling and Simulation

The system used for the simulations in this study can be seen in Figure 3. Similar systems have been used in several studies for the recovery of low-grade waste heat [15,16,32]. It is composed of two turbines, two evaporators, a condenser, a pump, and an electric generator. The system uses R245fa as the working fluid due to its favorable thermodynamic properties [9]. R245fa has a low boiling point (15.3 °C), which allows it to be used in low-temperature heat sources, such as the waste heat from small landfills. Additionally, R245fa exhibits a high specific heat, facilitating the transfer of a substantial amount of heat per unit mass. Furthermore, R245fa has low global warming potential, making it an environmentally friendly option. Other organic fluids that are used in ORCs include R123 and R134a [33]. R123 has a lower boiling point than R245fa but exhibits a higher critical temperature and lower thermal efficiency. On the other hand, R134a has a higher boiling point than R245fa, but it has a lower critical temperature and lower thermal efficiency. Both R123 and R134a have higher global warming potential than R245fa. Additionally, R245fa exhibits a high critical temperature, allowing for higher thermal efficiency in the ORC system and a lower required heat exchanger size. R245fa also has a relatively low toxicity level, making it safer to handle than other working fluids, such as R123, and it has lower flammability than R134a, making it safer to operate in case of leakage. In terms of specific application in small landfills in Antioquia, Colombia, R245fa would be a suitable choice due to its low GWP and relatively low cost. Its relatively low freezing point could also be beneficial for operation in the tropical climate of Colombia. Additionally, its high critical temperature would allow for higher thermal efficiency in the ORC system, which could increase the overall energy output and economic feasibility of the project [34].

The system operates by compressing the liquid R245fa in the pump (2). The pressurized liquid is brought to a superheated gas in the evaporators (3, 5), where the energy used to heat the refrigerant comes from the gases produced by the combustion of the biogas generated in the landfill. The super-heated gas is then expanded in the turbines (4, 6) to generate mechanical energy, which is subsequently converted into electrical energy by the generator. Finally, the expanded refrigerant is cooled to a saturated liquid state (1).

Table 1 presents the operating conditions of the system, which were obtained from similar systems [9,32,33]. Here, the terms n_T, n_p, and n_E correspond to the efficiency of the turbine, the efficiency of the pump, and the effectiveness of the evaporators, respectively. Moreover, the terms $\dot{m}_{bg}$, and LHV correspond to the mass flow rate and lower heating value of the biogas produced in the landfill, respectively The Buenavista landfill, situated in the north–central part of the department of Antioquia, serves as the recipient for waste generated in the municipality of Angostura. This landfill was selected for the case study due to its lack of infrastructure to harness the biogas that it generates [35]. The methodology proposed by Poma et al. [36] was used to estimate the mass flow of biogas generated in the landfill and its heating value. The necessary information for this calculation was obtained from reports published by the environmental entities of the department [35,37].

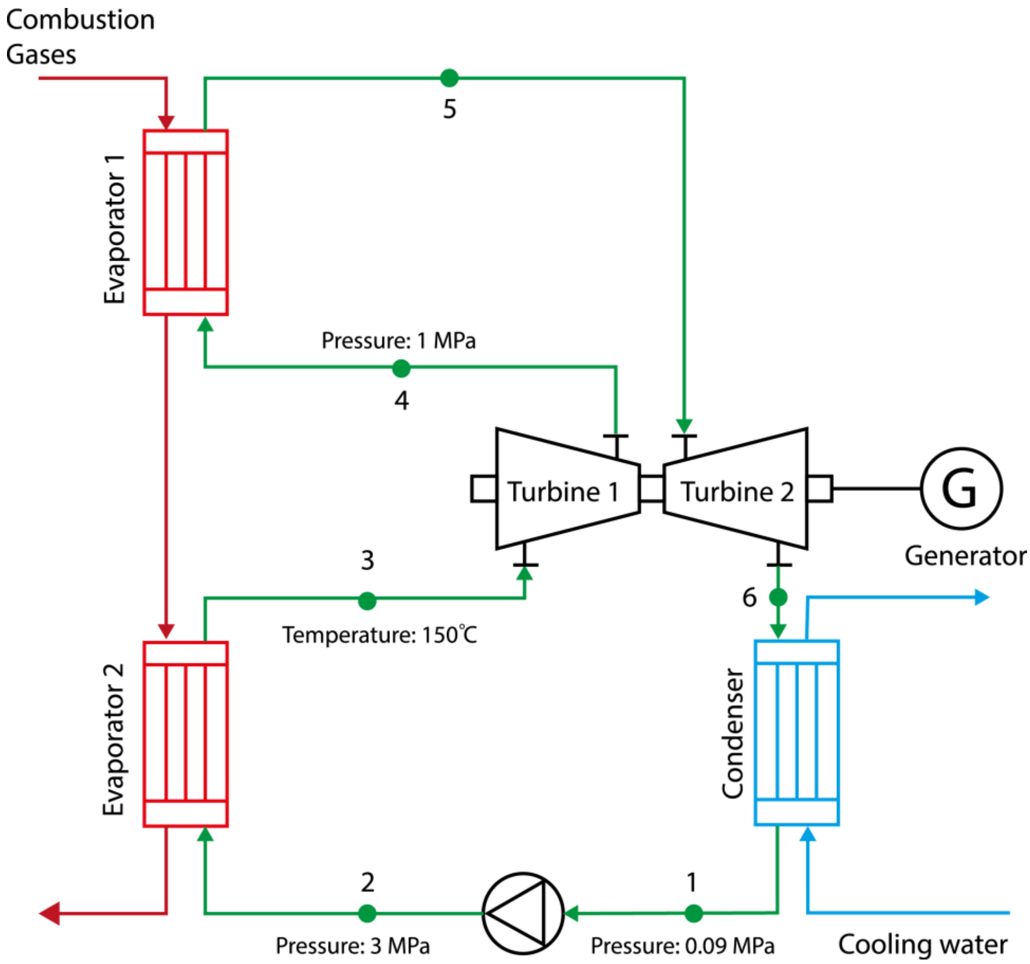

Figure 3. Proposed system.

Table 1. Initial operation conditions.

n_T	n_P	n_E	P_1 [MPa]	P_2 [MPa]	P_4 [MPa]	T_3 [°C]	$\dot{m}_{bg}$ [kg/s]	LHV [J/kg]
0.85	0.75	0.9	0.09	3	1	150	0.0016	27,766,500

For the thermodynamic simulation of the ORC cycle, thermodynamic properties, such as the enthalpy (h_1, h_3, h_5, in kJ/kg), entropy (S_3, S_5, in kJ/kgK), and enthalpy of saturated vapor (h_{4g}, h_{6g}) and saturated liquid (h_{4f}, h_{6f}), were calculated with the Open-Source Thermophysical Property Library CoolProp [38], based on the initial conditions stated in Table 1. The remaining variables were determined using the equations provided in Table 2 [32].

Table 2. Equations used for the thermodynamic simulation.

Variable	Equation	
Position 2	$h_{2s} = h_1 + v_1(P_2 - P_1),$	(1)
where v corresponds to the specific volume (in m^3/kg); the subscripts indicate specific states of the system, as depicted in Figure 3; and the subscript s represents the state that corresponds to an isentropic condition.		
	$h_2 = \frac{h_{2s} - h_1}{n_p} + h_1$	(2)
Position 4	$x_4 = \frac{S_3 - S_{4f}}{S_{4g} - S_{4f}},$	(3)
	where x represents the quality.	
	$h_{4s} = x_4\left(h_{4g} - h_{4f}\right) + h_{4f}$	(4)
	$h_4 = -\eta_T(h_3 - h_{4s}) + h_3$	(5)
Position 6	$x_4 = \frac{S_5 - S_{6f}}{S_{6g} - S_{6f}}$	(6)
	$h_{6s} = x_6(h_{6g} - h_{6f}) + h_{6f}$	(7)
	$h_6 = -\eta_T(h_5 - h_{6s}) + h_5$	(8)
Evaporators	$\dot{Q}_{in} = \dot{m}_{bg} * LHV$	(9)
	$\dot{m} = \frac{\dot{Q}in * \eta_E}{(h_5 - h_4) + (h_3 - h_2)}$	(10)
where $\dot{Q}in$ represents the amount of energy obtained from burning the gas produced in the landfill (in kW). The term $\dot{m}$ correspond to the mass flow rate of R245fa (in kg/s).		
Pump	$\dot{W}_P = \dot{m}(h_2 - h_1)$	(11)
Turbines	$\dot{W}_{T1} = \dot{m}(h_3 - h_4)$	(12)
	$\dot{W}_{T2} = \dot{m}(h_5 - h_6)$	(13)
	$\dot{W}_T = \dot{W}_{T1} + \dot{W}_{T2}$	(14)
Net Work Output	$\dot{W}n = \dot{W}_T - \dot{W}_P,$	(15)
where $\dot{W}$ corresponds to the power (in kW). The subscripts T and P correspond to turbine and pump, respectively.		
Cycle Efficiency	$\eta_{cyc} = \frac{\dot{W}_n}{\dot{Q}_{in}}$	(16)
Power Plant Efficiency	$\eta_{Pow} = \eta_E * \eta_{cyc}$	(17)
FTE	$FTE = \frac{1}{\eta_{pow}}$	(18)

3.2. Environmental Analysis

The objective of this study was to analyze the distribution of sensitive groundwater recharge zones in the department of Antioquia and to evaluate the risk of exposure of incinerators and landfills near these water bodies. To achieve these goals, we utilized both qualitative and quantitative data. Qualitative data were collected through documentary techniques, such as literary productions, public archives, and the written press [39]. These data provide insight into the perceptions and knowledge of the negative scenarios generated by the potential risk of leachate contamination from solid waste seeping into groundwater in the department [40,41]. On the other hand, in the context of quantitative data collection, we employed the use of the ArcGIS computer program, which incorporates the methodology of multi-criteria analysis. This approach focuses on a decision-making technique used to deliver a result regarding the status of groundwater quality, specifically, in this case, the recharge potential of the aquifer in the area [42]. This potential should be evaluated based on various overlapping criteria or different factors, which include key aspects, such as lithology, land use, slope, lineament density, and precipitation. To implement the multi-criteria analysis methodology, a collection of processed layers with information from the different main factors to analyze was carried out, as shown in Figure 4.

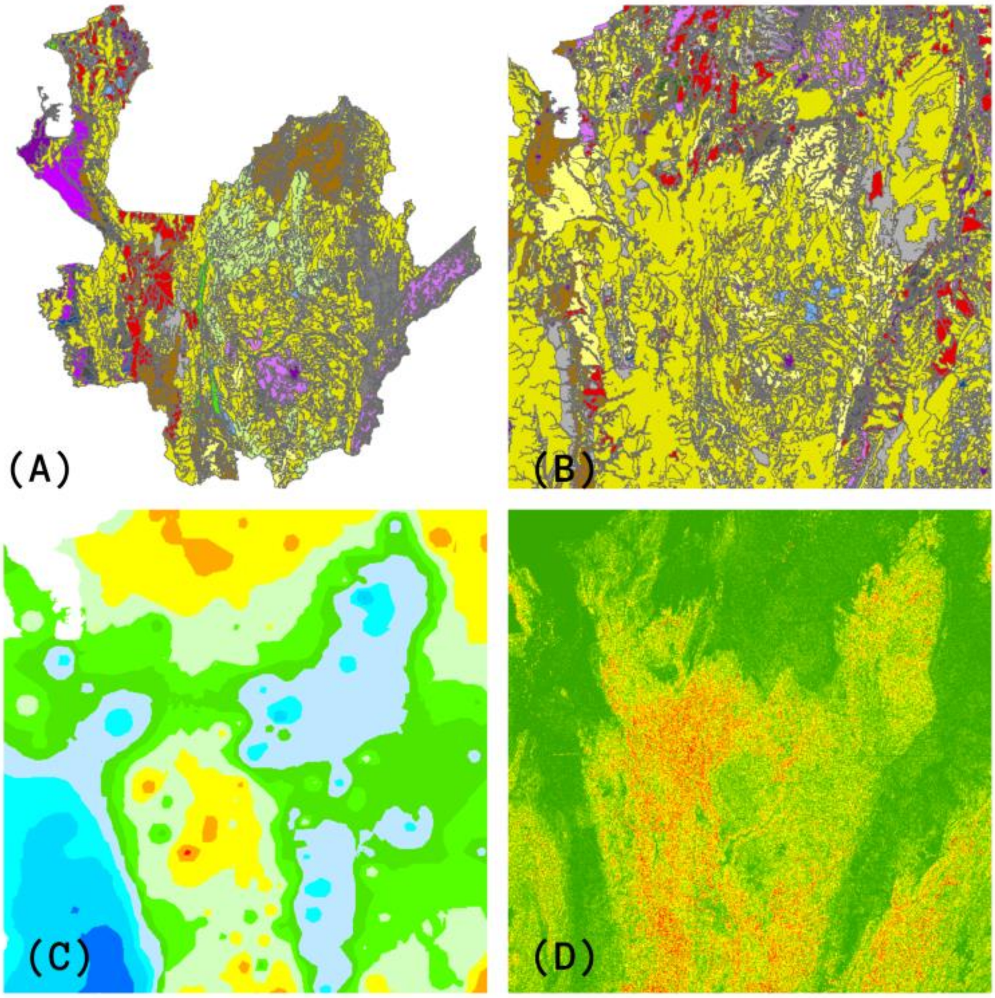

Figure 4. Processed layers processed illustrating the: (**A**) lithology; (**B**) land use; (**C**) precipitation; and (**D**) slope of the Antioquian territory.

With this approach, a weighted sum was determined for each pixel, which involves assigning weights to each criterion or factor to reflect its relative importance in the decision-making process, as shown in Table 3. Subsequently, the scores of each alternative are multiplied by the corresponding weights, and the results are summed to obtain a total score for each alternative, as shown in Equation (19).

$$\text{Weighted sum} = \text{Lithology (30\%)} + \text{Soil Use (25\%)} + \text{Lineation Density (20\%)} + \text{Slopes (15\%)} + \text{Drainage Density (10\%)} \quad (19)$$

Table 3. Categorization and weight for each variable.

Variable	Range	Value	Weight
Lithology1234567 (Permeability)	Very high	10	30%
	High	8	
	Moderate	6	
	Low	4	
	Very low	2	
Land use1234567 (Potential infiltration)	Very high	10	25%
	High	8	
	Moderate	6	
	Low	4	
	Very low	2	

Table 3. *Cont.*

Variable	Range	Value	Weight
Pending	<7°	10	20%
	7–15°	8	
	15–30°	6	
	30–40°	4	
	>40°	2	
Linearity density	Very high	10	15%
	High	8	
	Moderate	6	
	Low	4	
	Very low	2	
Precipitation	Very high	10	10%
	High	8	
	Moderate	6	
	Low	4	
	Very low	2	

Finally, the result of the weighted sum of each pixel establishes the map of the recharge potential of the aquifer in the department of Antioquia, considering the categorization table in the valuation of the weighted sum, as shown in Table 4.

Table 4. Categorized aquifer recharge potential.

Weighted Sum	Categorization	Meaning
0–2.5	(red)	Very low
2.5–5	(yellow)	Low
5–7.5	(cyan)	Moderate
7.5–10	(blue)	High

By combining both qualitative and quantitative data, we can obtain a comprehensive understanding of the situation. This process allows us to make well-informed decisions and develop effective strategies to address any groundwater quality issues in the department of Antioquia.

3.3. Economic Analysis

In this study, the economic feasibility of the ORC system is assessed using the net present value (NPV) method, which is widely recognized as a decision-making and appraisal tool in business practice [43]. The investment cost of the project was determined based on a reference plant [44]. Maintenance and operations costs were estimated at 3.5% of the investment cost per year. The energy sale and purchase price were calculated based on information published by the local energy provider [45] using the average cost of energy over the previous six months. To provide a comprehensive understanding of the variables considered in the NPV calculation, Table 5 presents a summary of the key factors used in determining the present net value of the project.

Table 5. Variables considered for the present net value of the project.

Parameter	Value
Investment cost of reference plant ($\$/kW_{el}$) [2]	2990
Operational and maintenance cost (% of inv. cost/year) [2]	3.5
Energy sale price ($/kWh) [3]	0.0845
Energy purchase price ($/kWh) [3]	0.13
Interest rate	12%

The equations used for the economic analysis can be seen in Table 6.

Table 6. Economic analysis equations.

Variable	Equation	
Investment	$\text{Investment} = \dot{W}n * 2990\frac{\$}{\text{kW}}$	(20)
Earnings	$\text{Earnings} = \dot{W}_T * (\text{hours in a year}) * 0.0845\ \$\frac{\$}{\text{kWh}}$	(21)
Costs	$\text{Cost} = \dot{W}_P * \quad (\text{hours in a year}) * 0.13\frac{\$}{\text{kWh}} + \text{Investment} * 3.5\%$	(22)
Cash flow	$\text{Cash flow} = \text{Earnings} - \text{Costs}$	(23)
Net present value	$\text{VPN} = \frac{\text{Cash flow}}{(1+\text{interest rate})^n}$	(24)

4. Results and Discussion

4.1. Thermodynamic Modeling and Simulation

Table 7 presents the results for a system with a biogas mass flow rate of 0.0016 kg/s and a lower heating value of 27,766,500 J/kg. Under these operating conditions, the system achieves a net rate of work of 64.238 kW with efficiency for the cycle of 14.48% and power plant efficiency of 13.03%.

Table 7. Results of the thermodynamic simulation.

Parameter	$\dot{W}_n$	FTE	n_{cyc}	n_{pow}
Results	64.328	7.6736	0.1448	0.1303

The performance of the cycle is directly impacted by the initial conditions, including temperature and operation pressure, as seen in Figure 5. It is observed that the net power output of the system exhibits an increasing trend with higher operation temperatures. For instance, as the temperature rises from 95 °C to 150 °C, the net power output of the system increases from 57.49 kW to 64.328 kW.

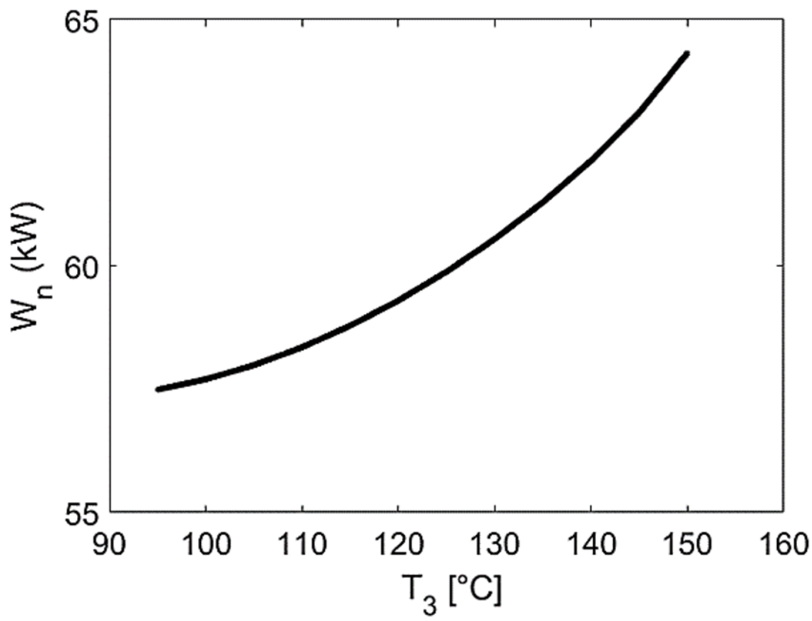

Figure 5. Effect of operation temperature in the net power output.

Figure 6 shows the effects of the operating temperature on both the cycle efficiency and the power plant efficiency of the system. The simulations indicate an increase in both efficiencies as the operating temperature rises. Specifically, over a temperature range of 95 °C to 150 °C, the cycle efficiency escalates from 12.94% to 14.47%, while power plant efficiency increases from 11.67% to 12.86%. These results are in accordance with previous studies [9,32,33], as increasing the operating temperature improves the thermal efficiency of the cycle [46]; this behavior is expected for thermal systems following the Carnot principle [46].

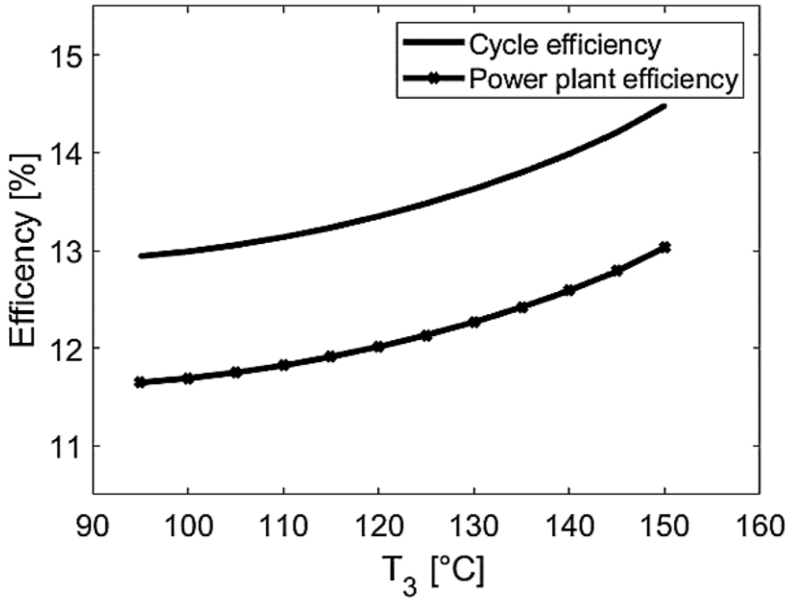

Figure 6. Effect of operating temperature on cycle and power plant efficiency.

The operating pressure of the cycle is indeed influential in determining the performance of the system, as illustrated in Figure 7. The simulations performed in this study showed that an increase in pressure has a positive effect on the net power output of the system. Specifically, the net power output of the system rises from 65.97 kW at 1.6 MPa to a maximum of 72.21 kW at 3 MPa, while at more than 3 MPa, the net power output of the system starts to decrease, with output of 71.84 kW at 3.2 MPa.

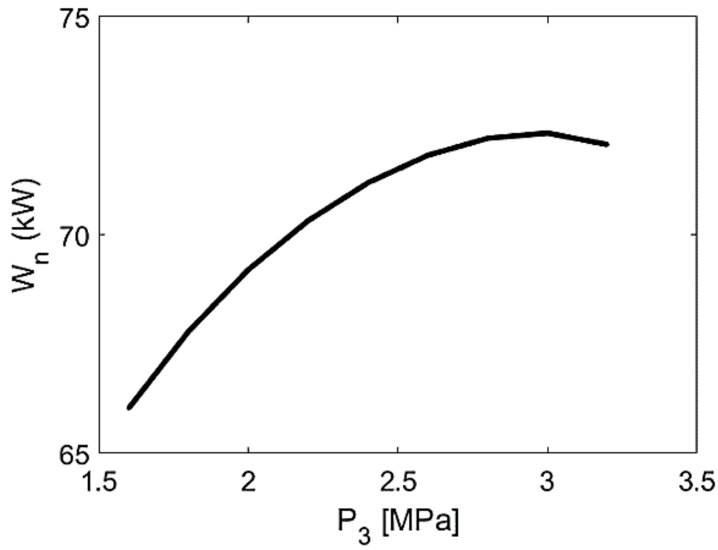

Figure 7. Effect of operating pressure on the net power output.

Pressure also exerts an influence on the thermal efficiency of the system, as shown in Figure 8. Both the power plant and cycle efficiencies go from 13.81% and 14.79% at 1.6 MPa to a maximum of 14.62% and 16.31% at 3 MPa, respectively, before declining to 14.52% and 16.18% at 3.2 MPa. The fall in efficiency observed for pressures greater than 3 MPa for the temperature range of 150 °C can be attributed to the working fluid reaching its critical point, which for R245fa is 3.65 MPa and 154.01 °C [38]. When the system operates near the critical point, the system starts operating with saturated liquid only, limiting the amount of energy that can be extracted by the turbines, as the differences in enthalpy for pressurized liquids are not as large compared to saturated vapor [46].

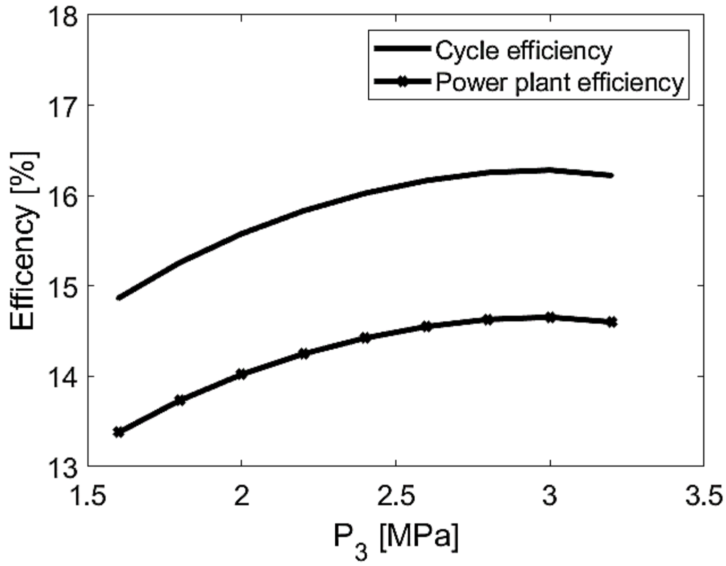

Figure 8. Effect of operating pressure on the efficiency of the system.

4.2. Environmental Analysis

Figure 9 illustrates the distribution of water bodies and aquifers and the location of water supply lagoons in some localities within the department of Antioquia. The department has 83 water catchment points, which are fed by the aqueduct networks of the Antioquian territory. The figure specifically highlights the Buenavista spillway, situated in the municipality of Angostura, at the intersection with the body of water that extends from the municipality of Caldas to the municipalities of Nechí and Segovia, with proximity to the Miraflores and Troneras reservoirs located in the municipalities of Angostura, Carolina, Gómez Plata, and Guadalupe. In Figure 9, these municipalities are represented by distinct red dots.

According to Figure 9, surface water bodies (streams, creeks, and rivers) near the Buenavista landfill are highly vulnerable to contamination due to the risk of leaks in the system and the influences of different meteorological seasons in the area. The contamination rate is likely to be higher during the wet season compared to the dry season [47]. Although the landfill has a gas and leachate collection system, it can still have impacts on the ecosystem [35]. In the event of structural failures at the landfill, runoff upstream of the site can interact with decomposing solid waste, leading to the generation of leachate that may harm the environment. The runoff not only permeates through the waste and into the soil, but it also, as it flows downstream, combines with other types of leachates in the area. Consequently, the contaminated water would flow downslope to the main rivers [48].

According to meteorological data from different stations, water balances for an average hydrological scenario and for representative periods indicate recharge magnitudes of 1330 mm/year and 2730 mm/year, respectively, for the water captured from the Angostura municipality [49]. Monthly variations indicate that, under average hydrological conditions, maximum recharge values occur mainly in October, while critical minimums are observed in January [49]. These data illustrate the importance of protecting water resources, specifically the water bodies surrounding the landfill, to ensure the quality of water for human consumption.

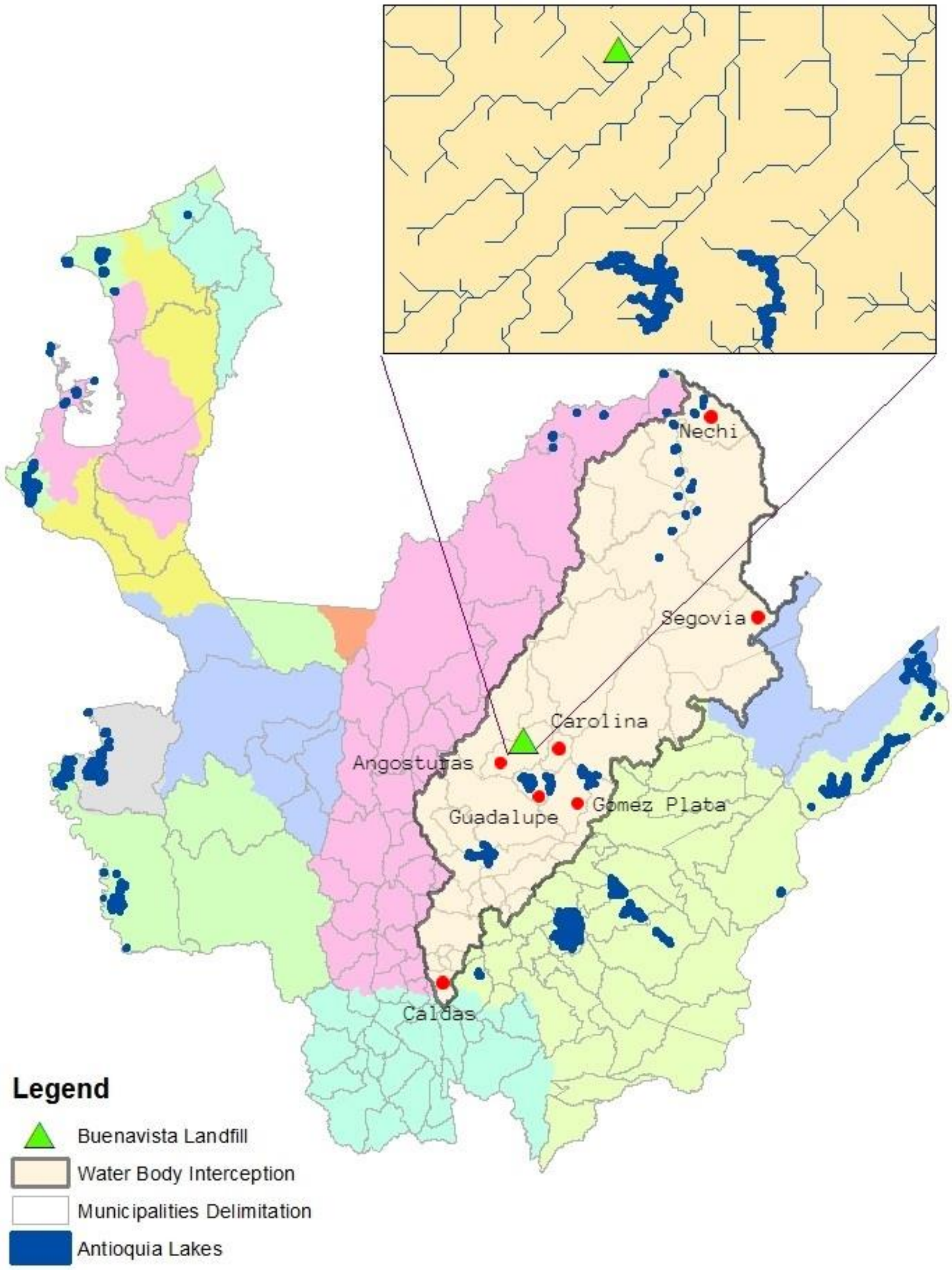

Figure 9. Water mass distribution and water supply network in Antioquia.

On the other hand, the spatial distribution of the hydrogeological units, the geomorphological attributes of the landscape, the hydrography, the type of cover, the hydraulic characteristics of the soils, and the hydrometeorological conditions are factors that condition the recharge of an aquifer system [50]. Concerning the Buenavista landfill, three sources of recharge were identified. First, there is recharge distributed throughout the length and width of the plain caused by direct infiltration of rainwater. Second, recharge occurs through hydraulic interaction between the two bodies of water formed around the mentioned municipalities. Last, indirect lateral recharge from the metamorphic bedrock contributes to both the free aquifer and the confined aquifer [51]. Figure 10 shows the water recharge potential of the department of Antioquia, including the surroundings of the study area.

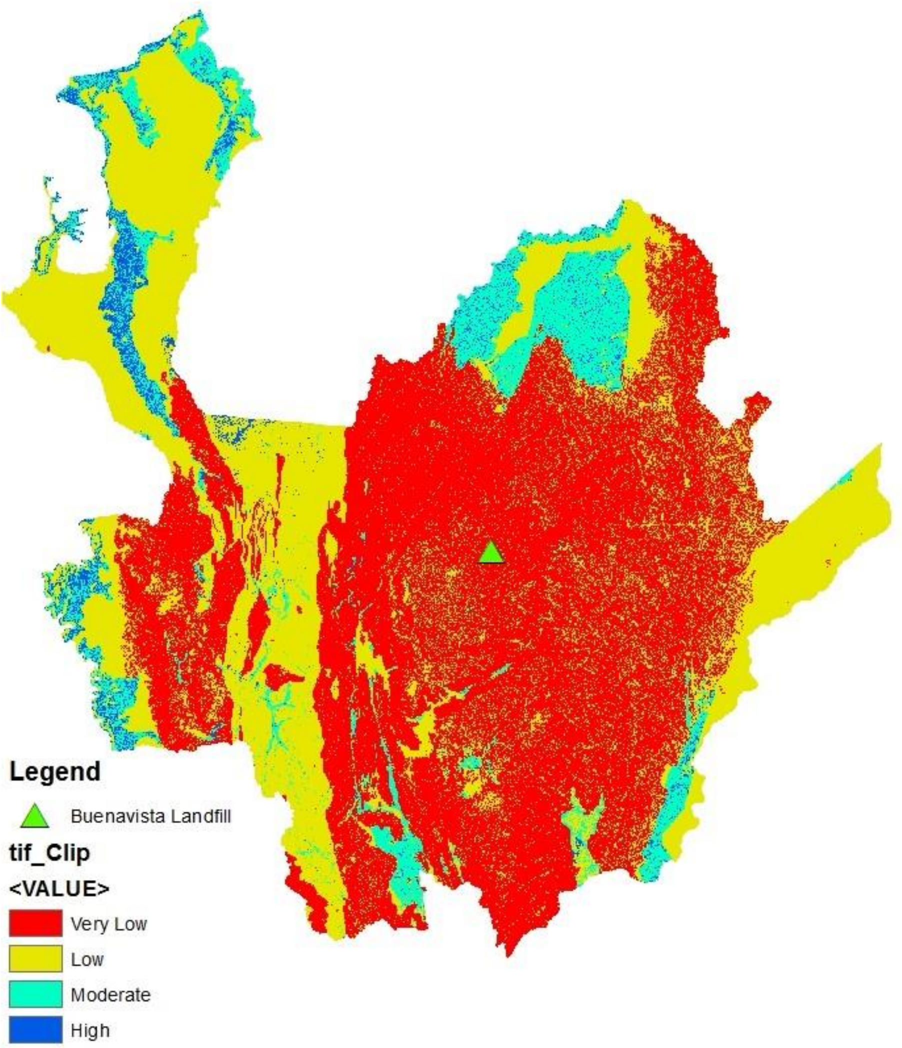

Figure 10. Potential of groundwater recharge in Antioquia.

From an environmental perspective, groundwater contamination poses greater challenges than surface water contamination due to the complexity of treating aquifers [52]. The likelihood of structural failure in a landfill leading to negative effects on the water quality of nearby water bodies and reservoirs is high, potentially rendering the water unsafe for human consumption [53]. However, the potential for groundwater recharge depends on various factors, such as rock type, soil type, vegetation cover, slope, and land use of the area, leading to different interactions compared to surface water [50].

With regard to Figure 9, the Buenavista landfill is situated in areas with low potential for groundwater recharge, indicating a minimal risk of aquifer contamination due to the low infiltration rate in the terrain. This terrain can be seen in the steep slopes of the study area [37], which impede groundwater transport by promoting runoff, being one of the main factors influencing leachate infiltration [54]. The geological characteristics of the area are typified by a weathered Antioquian batholith morphology known for its low porosity and low permeability, which hinder and limit the passage of discharges through them [55,56]. Finally, the level of rock soil and hydrogeological properties are important for establishing criteria and making decisions, and the absence of geological faults, fractures, and subway erosion in the municipality of Angostura makes it difficult for leachate to enter the groundwater through these pathways [56,57].

On the other hand, the Colombian government has conducted an analysis of the water quality in reservoirs, tributaries, and groundwater, which has met acceptable standards in accordance with environmental regulations [58]. Therefore, there have been no reported damages caused by the Buenavista landfill that could affect the water quality in the municipality and surrounding areas. However, proper management and oversight of the landfill are crucial to minimize environmental and health risks. Mitigation measures, such as clean-up and leachate treatment, as well as monitoring systems to detect and control contamination, should also be implemented to minimize the environmental impact. In conclusion, it is essential to protect and effectively manage the landfill to ensure the water quality and environmental well-being in the region.

4.3. Economic Analysis

The net present value of the ORC system was calculated using an investment cost of \$192, 340 USD. This investment was made at the start of the project during the construction phase and is based on a net output power of 64.328 kW. Earnings were determined by calculating the turbine output at 67.6404 kW per year. The costs of the project, including annual operation and maintenance expenses, as well as the cost of energy purchased for a 3.31 kW pump, were also considered and are detailed in Table 5.

The analysis showed that the ORC system is profitable over a 10-year period, with a net present value of \$31, 208 USD. Despite the initial investment of \$192, 340 USD, the project can recover its cost within five years. The profitability of the system can be attributed to its connection to the Colombian interconnected system of electric energy transmissions, which allows for the continuous injection and sale of energy throughout the country. Considering the current state of the global economy, the system could be even more profitable since the interest rate in Colombia has risen from 4% to 12% over the past year [59]. If the economic study had been conducted using the 4% interest rate that was in effect in January 2021, the net present value of the project would have been \$128, 564 USD.

As illustrated in Figures 6 and 8, the selection of the operating temperature and pressure significantly influences the economic performance of the project. An increase in temperature enhances the thermal efficiency of the cycle, leading to a higher net present value of the project, as shown in Figure 11, because the system can generate more energy with little to no additional cost. Consequently, the project's net present value increases from \$22, 140 USD to \$29, 024 USD when the temperature in state 3 increases from 90 °C to 150 °C.

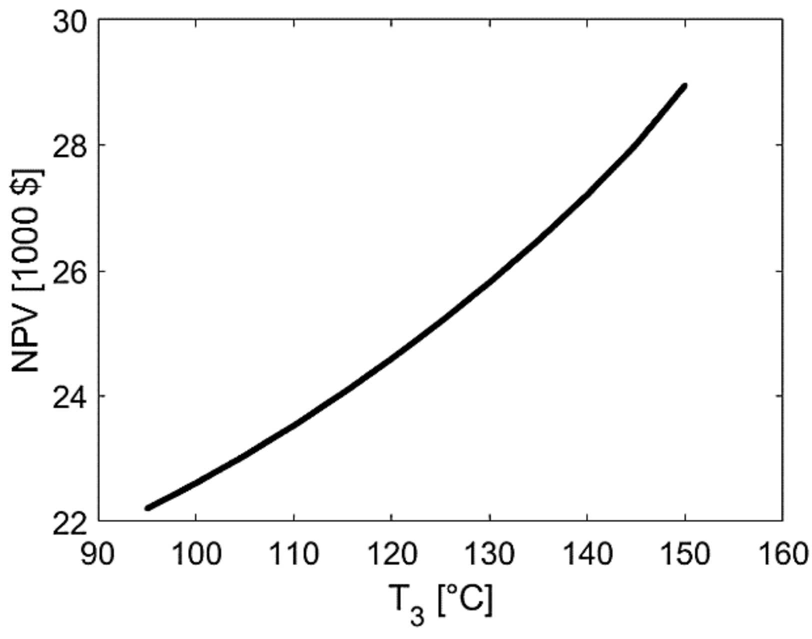

Figure 11. Effect of operating temperature on the net present value of the project.

Pressure also has an effect in the net present value of the project. As pressure increases, the thermal efficiency of the system improves, allowing the turbines to extract more energy.

However, the sizes of the turbines and pump also increase with pressure, causing the initial investment and the cost of energy for the pump to increase as the system becomes more efficient [46], as shown in Figure 12. The present value for this project has a maximum of $36,786 USD at 2.6 MPa, indicating that this pressure level is the most economically viable for the system. Pressures higher than 2.6 MPa may enhance the thermal efficiency and energy production of the system, as shown in Figures 7 and 8. However, from an economic standpoint, these higher pressures may not be optimal when considering the cost of the project.

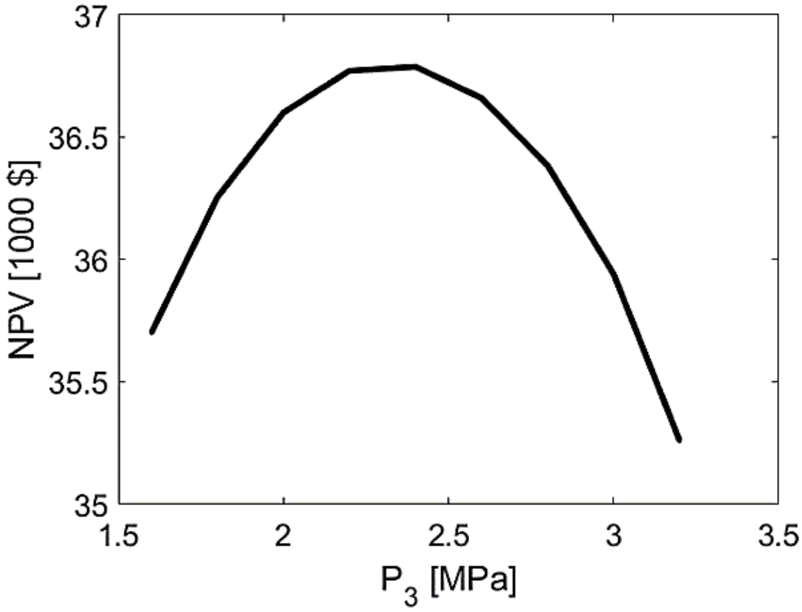

Figure 12. Effect of operating pressure on the net present value of the project.

5. Conclusions

In this study, we performed a simulation of an organic Rankine cycle (ORC) as a potential solution for harnessing the energy from the combustion of methane gas produced by small landfills in Antioquia, Colombia, with a focus on the municipality of Angostura. The proposed ORC system consisted of two evaporators, two turbines, a condenser, a pump, and a generator. To evaluate the system's performance, a sensitivity analysis was carried out to examine the influences of pressure, temperature, and mass flow on the net power output and efficiency of the ORC system.

The results showed that the ORC system is both thermodynamically and economically feasible. The system demonstrated a net power output of 64.33 kW and a power plant efficiency of 13.03%. With an investment cost of 192,340.00 USD, the project was found to have a positive net present value of 31,208.00 USD over a 10-year period, indicating its profitability. The sensitivity analysis revealed that temperature and pressure have direct influences on the system's performance and on the economic viability of the ORC system. Increasing the temperature and pressure resulted in higher net power output, indicating the importance of optimizing these operating parameters to maximize system efficiency and energy production.

In terms of environmental impact, the study found that the geomorphological characteristics of the municipality of Angostura allow for low infiltration of discharge into the phreatic levels, reducing the risk of groundwater contamination from landfill activities. However, there is a potential risk to surface water bodies due to the transport of leachates.

In conclusion, the implementation of an ORC system for the utilization of methane gas produced in small landfills in Antioquia, Colombia, presents a promising and viable solution for sustainable waste and energy management, providing economic benefits while minimizing the environmental footprint. Further studies should be carried out to optimize the performance of the ORC system and to evaluate the potential risks and benefits in different regions of Antioquia under different operating conditions.

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