A Comparison of the Co-Treatment of Urban Wastewater and Acidic Water Using a Ternary Emergy Diagram

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Abstract: The Pasco region in Peru is an area that has historically been polluted by mining activity and population growth. As a result, there is an increased production of urban wastewater and acidic water that contaminate local lakes such as Quiuilacocha and Patarcocha. The construction of a treatment plant that can treat the different types of wastewaters has not yet been studied, and its sustainability has not yet been evaluated. The objective of this research was to predict the sustainability of co-treatment systems in different scenarios between urban wastewater and acidic water, expressed in terms of a ternary emergy diagram. The design of the co-treatment plant was carried out at an inflow of 10 L/s. The first scenario (Treatment I) has a primary settler for the mixture of urban wastewater and acidic water, while the second scenario (Treatment II) involves a settler and a subsurface artificial wetland, and the third scenario (Treatment IIIa and IIb) presents a settler, an electrocoagulation system and a secondary settler; this scenario differentiates between the use of urban wastewater and eutrophicated water from Patarcocha Lake. The results of the ternary diagram show the contributions of the fractions of renewable resources from Treatment I (69%), from Treatment II (65.7%), from Treatment IIIa (61.6%), and from Treatment IIb (21.8%); the fractions of non-renewable resources in Treatment I (26.13%), Treatment II (24.13%), Treatment IIIa (23.33%), and Treatment IIb (9.50%); and the fractions of imported inputs in Treatment I (4.84%), Treatment II (9.37%), Treatment IIIa (15.04%), and Treatment IIb (68.72%). It is concluded that the use of a co-treatment system for urban wastewater and acidic water is sustainable in the long term when using an electrocoagulator or an artificial wetland.

Keywords: sustainability; eutrophication; emergy; exergy

1. Introduction

As populations grow, water resources become more limited, resulting in greater ecological impacts on local ecosystems. Therefore, it is important to adopt a comprehensive understanding of contaminated water treatment systems in order to develop integrated solutions and be able to improve their operational efficiency [1]. In Peru, the province of Pasco is a historical site that has been negatively affected by mining activities, affecting its water resources through acidic water drainage generated by historical environmental liabilities. Likewise, local lakes undergo significant eutrophication, generating effects on human health and plant and aquatic species [2]. Currently, urban effluents do not have an urban wastewater treatment plant [1].

The nature of the problem of acid mine drainage is that it has two types: acid mine drainage and acid rock drainage [2]. Both are produced to a greater extent due to the...
oxidation of minerals, such as pyrite (FeS$_2$), when they come into contact with air and water, generating sulfuric acid, sulfates, metals such as dissolved iron, and other products [2] characterized by high acidity and a high content of toxic metals and sulfates [3]. In addition, their origin is also associated with active or abandoned polymetallic mines, waste rock piles, tailing piles, subway mines, and soils near coal mines [4]. Due to its low pH, acid drainage (AD) interacts with rocks containing different types of minerals that easily cause the solubility of various toxic metals, such as arsenic, cadmium, zinc, copper, lead, etc. [5].

On the other hand, urban wastewater (UWW) represents a serious environmental problem and is characterized by microbial pathogens, concentrations of inorganic and organic matter, and high concentrations of organic and inorganic matter [6], among which phosphorus and ammonium stand out as components that represent an environmental problem [7] associated with the eutrophication of surface waters [8]. In view of these problems, there are methods or alternatives that have been developed for the treatment of acid drainage and urban wastewater independently. Acid drainage treatments can be classified as active and passive types [9]. Among the active methods are neutralization treatment with lime to precipitate metals and sulfates [5]; treatment with limestone [10]; adsorption [11]; membrane technologies [11]; electrodialysis [12]; advanced oxidation [13]; and electrocoagulation [14]. The passive treatment methods include wetlands [15], anoxic limestone drains [16], and sulfate reduction bioreactors [17]. Urban wastewater is treated by employing various physicochemical alternatives, such as adsorption [18], coagulation–flocculation [19], filtration [20], electrocoagulation [21], and biological alternatives such as anaerobic membrane bioreactors [22], microalgae [23], moving bed biofilm reactors [24], and activated sludge [25], among others.

In response to the problems posed by acid drainage and urban wastewater, novel alternatives based on co-treatment have been developed [26], which involve the mixing of these two types of wastewater in order to remove pollutants from both effluents by taking advantage of the synergy that exists between the components of both wastewaters, such as iron and phosphorus [27]. Using phosphate-rich effluents, such as urban wastewater, is an innovative way to treat acid drainage, since it has been reported that trivalent (Fe$^{3+}$ and Al$^{3+}$) and divalent (Mg$^{2+}$, Ca$^{2+}$ and Mn$^{2+}$) ions contained in acid mine drainage have a strong affinity for the phosphates (PO$_4^{3-}$) contained in urban wastewater [28], forming precipitates that remove contaminants [29], while the neutral or slightly basic pH of urban wastewater can promote the precipitation of metals contained in acid mine drainage [30], and solids, including pathogens, can be reduced [31]. In addition, many metals of interest can bind to the organic ligands present in urban wastewater [32]. Co-treatment, in recent years, has been applied in conjunction with treatments such as the use of wetland [28], batch sulfidogenic bioreactors [33], anaerobic reactors [31], etc.

However, according to [34], the co-treatment of acid drainage and urban wastewater shows its maximum contribution as a primary treatment, and it needs additional treatments to reduce other pollutants such as sulfates and to improve pH regulation. Therefore, these technologies need to be accompanied by active or passive treatments, requiring a variable use of energy and resources for their operation and maintenance. To meet the urgent need for its sustainable transformation, the overall performance of the co-treatment system as an emerging technology must be evaluated. However, in most of the reported cases, too much emphasis is placed on experimental and pilot studies, with zero attention being paid to environmental performance evaluation. In addition, the absence of standardized assessment systems, which are quite crucial to address key information on environmental impacts, impedes the description of environmental performance and ecological impacts in a co-processing system. To integrate environmental performance into the framework of the co-processing system, emergy synthesis, which takes into consideration both the natural properties and economic characteristics of a system, provides a promising solution.

Emergy analysis is a method that uses a common unit to measure and compare different resource inputs. This provides a single, complete, and comprehensive measure of a system’s total resource use. Emergy also accounts for the work carried out by nature to
produce the natural capital (water, emergy, minerals, etc.) on which the products or services entering the system are based, as opposed to traditional economic accounting, which accounts primarily for the human labor required to produce a product or service [35]. An emergy assessment provides the only common measure equipped to explore the behavior of a system as a whole; therefore, one can observe and optimize the interactions between subcomponents and assess their sustainability [36]. This technique allows for a comparison of various wastewater treatment models using indices to assess their sustainability [37].

In this research, ternary emergy diagrams are presented as graphical tools to assist in environmental accounting and environmental decision making based on emergy analysis. Ternary diagrams are called tools rather than graphical representations because they not only offer possibilities for data interpretation, but also allow data processing [38]. Ternary diagrams, which are widely used in areas such as chemistry, geology, and metallurgy, allow the use of the inherent properties of triangular diagrams to assess a system’s dependence on renewable and non-renewable inputs, environmental support for dilution and process emission reduction, and system efficiency [38]. The rapid visualization of the emergy accounting data allows processes and systems with and without ecosystem services to be compared, allows improvements to be assessed, and allows a system’s performance to be tracked over time.

The objective of this study is to evaluate the sustainability of four scenarios in the co-treatment of urban wastewater and acid drainage, projected at a real scale in Pasco-Peru, using an emergy diagram as a tool to facilitate the analysis and evaluation for decision making and to show improvement strategies for its applicability.

2. Materials and Methods

2.1. A Description of the Case Study

In Peru, the city of Pasco is located at an altitude of 4360 m above sea level and has an average perimeter of 1400 m [39]. This region is home to large reserves of water resources [1]. In the Pasco region, there is a significant negative impact of mining waste from the past, as well as catastrophic incidents in local ecosystems with serious impacts, causing a disturbance in the balance of the natural and social environments [40]. The notable effect of acidic waters generated by environmental liabilities in Pasco has led to a modification in surface and subway watercourses, as well as an alteration in the soil quality and a significant transformation in the landscape. Companies such as Aurex, Cerro SAC, and El Brocal discharged their industrial wastes into surface water environments, such as the Yanamate and Quiulacocha lakes (Figure 1), which, today, have become acid water and tailing deposits [40]. On the other hand, due to the high population of residents generated by mining activities, the disposal of untreated urban wastewater has become an urban management problem. Wastewater from the central and eastern parts of the city, which are located in the main commercial centers and hotels, is discharged to Patarcocha Lake, causing this lake to have a high rate of contamination [41].

2.2. Characterization of Wastewater and Acidic Water

Urban wastewater and acidic wastewater generate input as renewable and non-renewable resources as emergy flows. The initial characterizations of urban wastewater, eutrophicated lake water (Table 1), and acidic water from Quiulacocha Lake (Table 2) were used to determine estimates of emergy input.

2.3. Study Scenarios

This research analyzed four scenarios projected for the operation of a co-treatment plant for urban wastewater, eutrophicated water, and acidic water using a combination of active (with emergy costs) and passive (without emergy costs) unit processes; this approach allows the direction of a future development to be determined and allows the construction of a full-scale co-treatment plant in Pasco-Peru. The unit processes and sub-processes
that make up the co-processing plant, as well as its construction and operation, will help determine the emergy analysis and measure sustainability.

Figure 1. Location map of study area.

Table 1. Characterization of urban wastewater and eutrophicated water from Lake Patarcocha.

<table>
<thead>
<tr>
<th>N°</th>
<th>Parameter</th>
<th>Concentration (mg/L)</th>
<th>Urban Wastewater</th>
<th>Eutrophicated Water from Lake Patarcocha</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BOD₅</td>
<td>151.20</td>
<td>66.50</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>COD</td>
<td>255.50</td>
<td>111.30</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Total phosphorus</td>
<td>8.50</td>
<td>5.46</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Sulfates</td>
<td>500.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>pH</td>
<td>7.30</td>
<td>8.81</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Nitrate</td>
<td>3.15</td>
<td>1.66</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Nitrite</td>
<td>0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Ammonia nitrogen</td>
<td>0.01</td>
<td>1.30</td>
<td></td>
</tr>
</tbody>
</table>

N and E: Universal Transverse Mercator coordinates, north and east, respectively; N°: parameter number.

2.3.1. Treatment I

Figure S1 shows Treatment I as a general scenario that proposes to evaluate the main unit process with a primary settler. This primary settler allows for the mixing of acidic water and urban wastewater. This primary settler has a tank for the waste sludge generated. The flow rate of the combined wastewater entering the settler from the equalizer is 10 L/s, and the volumetric mixing ratio of acidic and urban wastewater is 1/7 (v/v), respectively.
Table 2. The characterization of the acidic water of the contaminated Quiulacocha Lake.

<table>
<thead>
<tr>
<th>N°</th>
<th>Parameter</th>
<th>Concentration (mg/L)</th>
<th>N°</th>
<th>Parameter</th>
<th>Concentration (mg/L)</th>
<th>N°</th>
<th>Parameter</th>
<th>Concentration (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sulfate</td>
<td>6000.00</td>
<td>13</td>
<td>Total Cadmium</td>
<td>0.0001</td>
<td>24</td>
<td>Total Nickel</td>
<td>0.001</td>
</tr>
<tr>
<td>2</td>
<td>pH</td>
<td>1.80</td>
<td>14</td>
<td>Total Calcium</td>
<td>284.81</td>
<td>25</td>
<td>Silver Total</td>
<td>0.005</td>
</tr>
<tr>
<td>4</td>
<td>Total Iron</td>
<td>1316.65</td>
<td>15</td>
<td>Total Cesium</td>
<td>0.02</td>
<td>26</td>
<td>Total Potassium</td>
<td>8.19</td>
</tr>
<tr>
<td>5</td>
<td>Total Zinc</td>
<td>1.02</td>
<td>16</td>
<td>Total Cobalt</td>
<td>0.002</td>
<td>27</td>
<td>Total Selenium</td>
<td>0.001</td>
</tr>
<tr>
<td>6</td>
<td>Total Copper</td>
<td>2.69</td>
<td>17</td>
<td>Total Chromium</td>
<td>0.0003</td>
<td>28</td>
<td>Total Silica</td>
<td>22</td>
</tr>
<tr>
<td>7</td>
<td>Total Lead</td>
<td>335.87</td>
<td>18</td>
<td>Total Phosphorus</td>
<td>4.6</td>
<td>29</td>
<td>Total Sodium</td>
<td>20.39</td>
</tr>
<tr>
<td>8</td>
<td>Total Arsenic</td>
<td>0.002</td>
<td>19</td>
<td>Total Lithium</td>
<td>0.12</td>
<td>30</td>
<td>Total Titanium</td>
<td>0.0007</td>
</tr>
<tr>
<td>9</td>
<td>Total Aluminum</td>
<td>19.59</td>
<td>20</td>
<td>Total Magnesium</td>
<td>1023.72</td>
<td>31</td>
<td>Total Uranium</td>
<td>0.005</td>
</tr>
<tr>
<td>10</td>
<td>Total Barium</td>
<td>0.0002</td>
<td>21</td>
<td>Total Manganese</td>
<td>498.94</td>
<td>32</td>
<td>Total Vanadium</td>
<td>0.0002</td>
</tr>
<tr>
<td>11</td>
<td>Bismuth Total</td>
<td>0.009</td>
<td>22</td>
<td>Total Mercury</td>
<td>0.001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Total Boron</td>
<td>0.002</td>
<td>23</td>
<td>Molybdenum</td>
<td>0.001</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

N and E: Universal Transverse Mercator coordinates, north and east, respectively; N°: parameter number.

2.3.2. Treatment II

Figure S2 shows Treatment II as a scenario that evaluates a co-treatment system consisting of a primary settler and a horizontal subsurface wetland. Treatment with a subsurface artificial wetland would allow for a substantial improvement in parameters that are not removed using the primary settler alone, such as sulfates, as well as better pH regulation. The flow rate of the combined wastewater is 10 L/s, and the volumetric mixing ratio of acidic and urban wastewater is 1/7 (v/v), respectively.

2.3.3. Treatment IIIa and IIIb

Figure S3 shows treatment scenarios IIIa and IIIb. These scenarios have main unit processes, such as a primary settling tank, followed by an upflow electrocoagulator with cylindrical electrodes and then a secondary settling tank. This design has the particularity of having sub-processes, such as sludge tanks and a bed for sulfate recovery from electrocoagulation. The difference between the two types of treatment is their use of urban wastewater (IIIa) and eutrophicated wastewater from Patarcocha Lake (IIIb). This differentiation is necessary to understand sustainability in the change in resource that contributes, along with phosphate, to co-treatment with greater accessibility. The flow rate of the combined wastewater is 10 L/s for both treatments, the volumetric mixing ratio of acid and urban wastewater is 1/7 (v/v) for Treatment IIIa, and the mixing ratio of acid and eutrophicated lake water is 1/15 (v/v) for Treatment IIIb, respectively.

2.4. Estimation of Sustainability Indexes of Emergy

Emergy is quantified as the sum of all emergy inputs required directly or indirectly by a process to provide a given output when the inputs are expressed in the same form (or type) of emergy, usually solar emergy. Thus, emergy is obtained by summing all the inputs (expressed in equivalent emergy of a single form, such as solar emergy) used in the process chain that produced the output [25].

On a unit basis, one joule or gram of a given output is produced by dissipating a given amount of equivalent solar emergy. The amount of input emergy (expressed as solar emergy) per unit of output emergy is called solar transformation; Equation (1) shows the equation for transforming available emergy into emergy.

\[ Em = AE \times k \]  

(1)

where
\( En = \text{emergy, measured in solar joules (seJ)}; \)
\( AE = \text{available emergy (J)}; \)
\( k = \text{solar transformability (seJ/J)}. \)

**Emergy-Based Sustainability Indices**

As illustrated in Figure 2, the different phases of growth and decline of a system can represent a human economy where there is a growth, transition, and decline in driving emergy sources. Practices and processes that are characteristic during the growth phase may not be sustainable during transition or decline because they rely on non-renewable energies that are declining. On the other hand, practices that are sustainable during decline, because they do not rely on non-renewable sources, are likely to be uncompetitive with rapidly growing systems [25].

![Figure 2. Phases of growth of an economic system.](image)

All system inputs are generally classified into three types: local renewable resources (R), such as sunlight, wind, and rain; local non-renewable resources (N), which refer to those available in limited quantity within the system boundaries, such as soil erosion and groundwater; and the import of goods and services (F), which include resources purchased by the economy, such as electricity, machinery, labor, etc.

- **Percentage of renewable emergy use (PR):** This indicates what percentage of the total usable emergy comes from renewable resources. A system that uses a high fraction of renewable resources is considered more sustainable in the long term [26].

  \[
  PR = \frac{R + FR + SR}{U} = \frac{R}{U} \tag{2}
  \]

- **Emergy Yield Ratio (EYR):** This measures the efficiency of the process in incorporating inputs acquired from the economy to exploit local resources. The higher the EYR, the greater the contribution to the economy per unit of emergy invested [26].

  \[
  EYR = \frac{U}{(FN + SN)} \tag{3}
  \]

- **Environmental Load Ratio (ELR):** The ELR measures the ratio of non-renewable resources (N) and the non-renewable fraction of inputs purchased by the economy (FN + SN) to the renewable resources employed in the system (R + FR + SR), including the renewable fraction of imported inputs. This value indicates the potential environmental impact and ecosystem stress due to the transformation process. As the ELR increases, the system becomes less sustainable [26].
\[ ELR = \frac{(N + F_N + S_N)}{(R + F_R + S_R + N)} \] (4)

**Emergy Investment Ratio (EIR):** This is the ratio of the investment of resources imported from outside of the system to local resources. It relates emergy coming from the economy to that coming from the environment. The higher the value, the greater the dependence on the economy, and the smaller the dependence on internal resources. This indicator evaluates whether the system is a user of resources from the economy compared to other alternatives. Therefore, a system with a lower ratio is more likely to prosper in the market [26].

\[ EIR = \frac{(F_N + S_N)}{(R + F_R + S_R + N)} \] (5)

**Emergy Sustainability Index (ESI):** This is an emergy sustainability index that measures the potential contribution of a process per unit of environmental load. This index reflects the overall sustainability of a production process, representing both economic and ecological compatibility [26].

\[ ESI = \frac{EIR}{ELR} \] (6)

### 2.5. Ternary Diagrams of Emergy

Ternary diagrams were proposed by Gibbs and Roozeboom for a mixed component analysis; commonly, there are three fractions or proportions that sum to 1 or three percentages that sum to 100. The constant sum constraint means that there are only two independent pieces of information [38]. A ternary emergy diagram has three components, R, N, and F (Figure 3), representing an equilateral triangle; each corner represents an element, and each side represents a binary system. The ternary combinations are represented by points within the triangle, and the relative proportions of the elements are given by the lengths of the perpendiculars from the given point to the side of the triangle opposite the appropriate element. Thus, the “composition” of any point plotted (for example, points 1 to 10 in Figure 3) in a ternary diagram can be determined (or any point can be plotted) by reading from zero along the basal line (axis) at the bottom of the diagram to 100% at the apex of the triangle [38].

![Figure 3. Ternary emergy diagrams.](image)

The ternary diagrams show important properties. When two different ternary compositions, represented by points P and Q within the triangle (Table 3), are mixed, the resulting composition will be represented by point X, which is called the “symergic” point [38].
Another important property of triangular diagrams is the importance of a straight line joining a vertex to a point on the opposite edge (Table 3). Any point along the indicated line represents a composition that is progressively poorer in N as it passes from A and B, but R and F remain present in the same initial proportion. Thus, if it is desired to represent the changing composition of a system, A, as the% N decreases, all that is needed is to draw a line from the apex, N, passing through point A. Any ternary system formed by adding or subtracting N from the above composition lies somewhere on this line, which is called the “sensitivity line” [38].

### Table 3. Properties of emergy ternary diagrams that function as auxiliary tools for emergy analysis.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Description</th>
<th>Illustration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource flow lines</td>
<td>The ternary combinations are represented by points within the triangle, and the relative proportions of the elements are given by the lengths of the perpendiculars from the given point to the side of the triangle opposite the appropriate element. These lines are parallel to the sides of the triangle and are very useful for comparing the use of by-products or resource processes.</td>
<td><img src="image" alt="Resource flow lines" /></td>
</tr>
<tr>
<td>Sensitivity lines</td>
<td>Any point along the straight line joining a vertex to a point represents a change in the amount of flow associated with the vertex. Any point along the line represents a condition in which the other two fluxes remain in the same initial proportion. For example, the system illustrated on the right is progressively poorer in N as it moves from A to B, but R and F remain in the same initial proportion.</td>
<td><img src="image" alt="Sensitivity lines" /></td>
</tr>
<tr>
<td>Synergy point</td>
<td>When two different ternary compositions, represented by points A and B inside the triangle, are mixed, the resulting composition will be represented by point S, called the “synergy point”, which is located somewhere on segment AB.</td>
<td><img src="image" alt="Synergy point" /></td>
</tr>
<tr>
<td>Sustainability lines</td>
<td>The graphical tool allows for lines indicating constant values of the sustainability index to be drawn. The sustainability lines start from the apex, N, in the direction of the RF side, allowing the division of the triangle into sustainability areas, which are very useful for identifying and comparing the sustainability of products and processes.</td>
<td><img src="image" alt="Sustainability lines" /></td>
</tr>
</tbody>
</table>

Extracted from [38].

### 3. Results

According to the calculated emergy flows in Table 4, Table 5 is developed, which shows that the four treatments have a low environmental load of ERL < 2; this is because the use of wastewater as a renewable and non-renewable natural resource does not generate stress in natural systems. By combining the wastewater and treating it, there is a double flow of treated water, as shown in Treatment I. The use of the combination of this wastewater alone generates a large contribution to the system as a natural resource and increases its emergy contribution at the outlet of the system so that, in the four treatment scenarios, it shows NRR > 1. Regarding the import of emergy to the system, the four treatment scenarios present EIR < 1, confirming that the import of emergy to the system is lower than the renewable and non-renewable energies used; therefore, the system is not stressed. On the sustainability index, there is a large difference in the four treatment systems. None of the four treatments presents an IS < 1; Treatment IIIb has an IS range of 1 < IS < 3, causing it to be considered as a sustainable system in the short term, while Treatments I, II, and III have an IS > 5, showing that the system is sustainable in the long term.
Table 4. Emergy flows for different co-treatment scenarios.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Scenario I</th>
<th>Scenario II</th>
<th>Scenario IIIa</th>
<th>Scenario IIIb</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>Renewable resources</td>
<td>2.59 × 10^19</td>
<td>2.59 × 10^19</td>
<td>2.59 × 10^19</td>
<td>1.12 × 10^19</td>
<td>seJ/year</td>
</tr>
<tr>
<td>N</td>
<td>Non-renewable resources (N + N + N)_{012}</td>
<td>9.79 × 10^18</td>
<td>9.79 × 10^18</td>
<td>9.79 × 10^18</td>
<td>4.9 × 10^18</td>
<td>seJ/year</td>
</tr>
<tr>
<td>N_0</td>
<td>Non-renewable resources for rural use</td>
<td>9.79 × 10^18</td>
<td>9.79 × 10^18</td>
<td>9.79 × 10^18</td>
<td>4.9 × 10^18</td>
<td>seJ/year</td>
</tr>
<tr>
<td>N_1</td>
<td>Non-renewable resources for urban use</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>Non-renewable resources directly exported</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>seJ/year</td>
</tr>
<tr>
<td>F</td>
<td>Fuel imports</td>
<td>3.16 × 10^15</td>
<td>6.52 × 10^15</td>
<td>8.49 × 10^15</td>
<td>1.26 × 10^18</td>
<td>seJ/year</td>
</tr>
<tr>
<td>G</td>
<td>Import of goods</td>
<td>4.42 × 10^17</td>
<td>4.93 × 10^17</td>
<td>6.15 × 10^17</td>
<td>1.89 × 10^18</td>
<td>seJ/year</td>
</tr>
<tr>
<td>P_{I2}</td>
<td>Services and other imported goods</td>
<td>1.37 × 10^18</td>
<td>3.19 × 10^18</td>
<td>5.7 × 10^18</td>
<td>5.7 × 10^18</td>
<td>seJ/year</td>
</tr>
<tr>
<td>P_{E1}</td>
<td>Emergy value of exported goods and services</td>
<td>2.97 × 10^19</td>
<td>2.97 × 10^19</td>
<td>2.97 × 10^19</td>
<td>2.97 × 10^19</td>
<td>seJ/year</td>
</tr>
</tbody>
</table>

Table 5. Emergy indicators for different co-treatment scenarios.

<table>
<thead>
<tr>
<th>Index Name</th>
<th>Expression</th>
<th>Scenario I</th>
<th>Scenario II</th>
<th>Scenario IIIa</th>
<th>Scenario IIIb</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imported energy flow</td>
<td>F + G + P_{I2}</td>
<td>1.81 × 10^18</td>
<td>3.69 × 10^18</td>
<td>6.32 × 10^18</td>
<td>8.85 × 10^18</td>
<td>seJ/year</td>
</tr>
<tr>
<td>Total energy inflows</td>
<td>R + N + F + G + P_{I2}</td>
<td>3.75 × 10^19</td>
<td>3.93 × 10^18</td>
<td>4.20 × 10^19</td>
<td>2.50 × 10^19</td>
<td>seJ/year</td>
</tr>
<tr>
<td>Total energy used, U</td>
<td>N_0 + N_1 + R + F + G + P_{I2}</td>
<td>2.77 × 10^19</td>
<td>3.93 × 10^18</td>
<td>3.22 × 10^19</td>
<td>2.50 × 10^19</td>
<td>seJ/year</td>
</tr>
<tr>
<td>Fraction of energy use</td>
<td>(N_0 + N_1 + R)/U</td>
<td>128.82</td>
<td>90.63</td>
<td>110.78</td>
<td>64.57</td>
<td>%</td>
</tr>
<tr>
<td>Imports minus exports</td>
<td>(F + G + P_{I2}) − (N_2 + P_{E1})</td>
<td>−2.79 × 10^19</td>
<td>−2.60 × 10^19</td>
<td>−2.34 × 10^19</td>
<td>−2.09 × 10^19</td>
<td>seJ/year</td>
</tr>
<tr>
<td>Import/export ratio</td>
<td>(F + G + P_{I2})/(N_2 + P_{E1})</td>
<td>0.06</td>
<td>1.24 × 10^{-1}</td>
<td>2.13 × 10^{-1}</td>
<td>0.3</td>
<td>%</td>
</tr>
<tr>
<td>Renewable used fraction</td>
<td>R/U</td>
<td>93.44</td>
<td>65.74</td>
<td>80.36</td>
<td>44.97</td>
<td>%</td>
</tr>
<tr>
<td>Fraction of imported services</td>
<td>P_{I2}/U_{2}</td>
<td>4.95</td>
<td>8.1</td>
<td>17.71</td>
<td>22.81</td>
<td>%</td>
</tr>
<tr>
<td>Fraction used being compared</td>
<td>(F + G + P_{I2})/U</td>
<td>0.086</td>
<td>0.094</td>
<td>0.196</td>
<td>0.354</td>
<td>%</td>
</tr>
<tr>
<td>Use per unit area</td>
<td>U/(area ha)</td>
<td>1.85 × 10^20</td>
<td>2.62 × 10^20</td>
<td>2.15 × 10^20</td>
<td>1.67 × 10^20</td>
<td>seJ/ha</td>
</tr>
<tr>
<td>Usage per person</td>
<td>U/population</td>
<td>4.70 × 10^14</td>
<td>6.68 × 10^14</td>
<td>5.46 × 10^14</td>
<td>4.24 × 10^14</td>
<td>seJ/person</td>
</tr>
<tr>
<td>Energy/dollar ratio</td>
<td>P = U/GDP **</td>
<td>1.24 × 10^8</td>
<td>1.77 × 10^8</td>
<td>1.45 × 10^8</td>
<td>1.12 × 10^8</td>
<td>seJ/USD</td>
</tr>
</tbody>
</table>

Area (ha) = 0.15; benefited population (Unit) = 588999; ** GDP (USD) = 2.22543 × 10^{11}.

Tables 6 and 7 shows that there is a significant variation in the use of renewable resources used for Treatment I (69%), Treatment II (65.7%), Treatment IIIa (52.87%), and Treatment IIIb (11.23%). Non-renewable resource use has the following order according to the amount of emergy used: Treatment I > Treatment II > Treatment IIIa > Treatment IIIb.

Figure 4 presents the ternary diagram constructed with the inputs from the different treatment scenarios. The subscripts used for the representation of emergy in a ternary diagram correspond to a distribution in functions of R, N, and F that refer to the percentage of renewable resources in the four synergic treatment scenarios.
Table 7. Emery indicators, %R, and relative values of %N and %F.

<table>
<thead>
<tr>
<th>Type of Treatment</th>
<th>Total Emergy (E+18 seJ/Year)</th>
<th>R (E+18 seJ/Year)</th>
<th>%R (E+18 seJ/Year)</th>
<th>N (E+18 seJ/Year)</th>
<th>%N (E+18 seJ/Year)</th>
<th>F (E+18 seJ/Year)</th>
<th>%F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment I</td>
<td>37.47</td>
<td>25.87</td>
<td>69.0</td>
<td>9.79</td>
<td>26.13</td>
<td>1.81</td>
<td>4.84</td>
</tr>
<tr>
<td>Treatment II</td>
<td>39.34</td>
<td>25.87</td>
<td>65.7</td>
<td>9.79</td>
<td>24.89</td>
<td>3.69</td>
<td>9.37</td>
</tr>
<tr>
<td>Treatment IIIa</td>
<td>41.97</td>
<td>25.87</td>
<td>61.6</td>
<td>9.79</td>
<td>23.33</td>
<td>6.31</td>
<td>15.04</td>
</tr>
<tr>
<td>Treatment IIIb</td>
<td>51.56</td>
<td>11.23</td>
<td>21.8</td>
<td>4.90</td>
<td>9.50</td>
<td>35.43</td>
<td>68.72</td>
</tr>
</tbody>
</table>

%R: amount of emergy from renewable flows; %N: amount of emergy from non-renewable flows, and %F: amount of imported emergy to system.

Figure 4. Ternary diagram and comparison of the different co-treatments.

The locations of the sustainability points in the ternary diagram show the spatial difference between the four treatment scenarios. The emergy contributions of the treatments show that Treatment I has the largest contribution to the socio-environmental-economic system (Figure 4). For more detail, the emergy contributions, according to the ternary diagram, show that the fraction of renewable resources decreased considerably in the last treatment. The %R of Treatment I was 69%, the %R of Treatment II was 65.7%, the %R of Treatment IIIa was 61.6%, and the %R of Treatment IIIb was 21.8%; the fraction of non-renewable resources (%N) remained almost constant, as it was 26.13% in Treatment I, 24.89% in Treatment II, 23.33% in Treatment IIIa, and 9.50% in Treatment IIIb; and the fraction of imported inputs (%F) increased, where it was 4.84% in Treatment I, 9.37% in Treatment II, 15.04% in Treatment IIIa, and 68.72% in Treatment IIIb.

4. Discussion

The combination of urban wastewater and acidic water has become a promising technology in wastewater treatment, maintaining its potential as a pretreatment [34]. The combination of these two wastewaters results in real synergies in treatment because they both have levels of contaminants that complement each other to achieve treatment [28]; so, on a practical level, conventional urban wastewater and/or acidic water treatment methods...
are often emery-intensive with higher operational and maintenance costs compared to passive treatment approaches or co-treatments [42,43], making this type of technology promising for sustainable and less-emery-intensive treatments [44].

The concept of combining urban wastewater treatment with acid drains has been studied for a long time; the authors of [45] first proposed the blending of both wastewaters to reduce pathogens due to a low pH and high metal concentrations from acid drainage, but paid little attention to the effectiveness of co-treatment and its potentials. The authors of [46] found that Escherichia coli populations were rapidly reduced when exposed to acid mine drainage. The authors of [47] manipulated the pH of water samples from the Monongahela River in West Virginia that contained domestic sewage-related microorganisms, finding a marked decrease in the microbial concentrations in low-pH samples. In addition, algae-based systems have been developed in waste stabilization ponds that treated synthetic acidic water and organic tannery effluent to achieve relatively high metal removal efficiencies [48]. These mixed effluent systems failed after a few months due to algal and metal toxicity, despite promising short-term performance [49] and microcosm laboratory studies, [49] where urban wastewater was used to create a high-pH, algae-rich effluent before mixing it with acid mine drainage, resulting in high efficiencies.

The co-treatment of acidic water and urban wastewater is a promising remediation approach. Studies such as [28] used a field-scale aerobically constructed wetland system to treat a low-strength secondary effluent (14 mg BOD5/L) and mine water (net alkaline with 3 mg Fe/L). The results showed that the treatment was successful in reducing Fe, ammonia, and BOD5. Ref. [50] investigated the co-treatment between acid mine drainage and secondary urban wastewater in an evaporation pond. They obtained results in water quality improvement and bacterial sulfate reduction. Ref. [51] suggested the use of acid mine drainage for phosphate removal from secondary wastewater effluent to control eutrophication in receiving waters. Ref. [52] tested the co-treatment of acid mine drainage and urban wastewater under aerobic conditions with the addition of limestone and concluded that the approach was a promising treatment method for removing metals and producing alkalinity. They investigated a four-stage passive system (clarifiers, Kaldnes, limestone, and wetlands) for the co-treatment of high-strength synthetic acid mine drainage (pH 2.6, acidity 1870 mg/L as CaCO3) and urban wastewater. They obtained promising results in the removal of BOD5, nutrients, and metals and a 5–12% sulfate reduction [52].

In this research, four (4) co-treatment scenarios were proposed, guaranteeing, according to previous experimental studies, that Treatment I, Treatment II, and Treatment IIIa have efficiencies greater than 90% [53] in a 1/7 ratio of acidic water and urban wastewater (v/v), and preliminary studies with Treatment IIIb with a 1/15 ratio of acidic water and eutrophicated water (v/v). The combination ratio coincides with the studies reported by [34,54]. The wastewater combination ratio determines the pollutant removal and the amount of inflow for each co-treatment scenario. The energy flow of urban and eutrophicated wastewater is determined by the pollutant concentration and water volume in the same way as acidic water, although for this research, urban and eutrophicated wastewater contribute as renewable resource flows, while acidic water contributes with a non-renewable energy flow.

For better practical information on the quality of inflows and outflows in the water treatment system, this study shows the sustainability indexes based on energy by means of an energy ternary diagram. The indicators developed in Table 3 allowed for the level of environmental sustainability of the different co-treatment systems to be identified. The environmental load ratio indices were 0.45, 0.52, 0.62, and 1.22 for Treatment I, Treatment II, Treatment IIIa, and Treatment IIIb, respectively; a low ELR value (low environmental load ELR < 2) suggests that the local renewable inputs are sufficient to meet the process demands compared to studies such as those using desalination plants [28] with high loads of 5.46, conventional urban water treatment plants [30] with an ELR of 57.2, and industrial wastewater treatment systems [55] with an ELR of 323.
The sustainability indexes in the different studies are highly variable according to the type of wastewater and the unit processes in the water treatment processes. This research has obtained, in its different treatments, a sustainability index (SI) in the range of 0.55–2.82 in comparison with the studies of the desalination plant that obtained an SI of 0.18 [56], being non-sustainable systems; however, the microalgae-based acid mine drainage treatment plant in a photobioreactor has an SI greater than 1, so they are systems of medium-term sustainability.

Figure 4 compares the co-treatment scenarios using a ternary diagram, where it is shown that the fraction of renewable resources decreased considerably in the last treatment, where the %R of Treatment I was 69%, the %R of Treatment II was 65.7%, the %R of Treatment IIIa was 61.6%, and the %R of Treatment IIIb was 21.8%; the fraction of non-renewable resources (%N) remained almost constant, as it was 26.13% in Treatment I, 24.89% in Treatment II, 23.33% in Treatment IIIa, and 9.50% in Treatment IIIb; and the fraction of imported inputs (%F) increased, as it was 4.84% in Treatment I, 9.37% in Treatment II, 15.04% in Treatment IIIa, and 68.72% in Treatment IIIb. The analysis of the ternary diagram was determined by the proportion of three different types of resources. The resource flow line, R, corresponds to the ELR emergy index; the closer the resource flow line R is to the F-axis, the higher the ELR and the higher the ecological environmental pressure of the co-treatment systems. The order of the ELR values was Treatment IIIb < Treatment IIIa < Treatment II < Treatment I. Therefore, co-treatment systems using urban wastewater as an input have the best environmental compatibility. Compared to Treatment IIIa, which also uses an active emergy system, this is considerably reduced, and the ELR of Treatment IIIb is the lowest. This shows that the treatment depends on the type of wastewater rather than the type of treatment processes as a whole, so all treatments with active and passive operation processes can be optimized in both economic and environmental aspects.

The analysis of the prediction of the sustainability direction in the ternary emergy diagram and the comprehensive analyses of the sensitivity and sustainability lines of the co-treatment systems can predict the future development direction of the co-treatment system. The sensitivity lines R and N are shown in Figure 4. According to the current development situation, there are two possible development directions for co-treatment systems. One is from the top to the bottom along the sensitivity line of non-renewable resources; the other is from the bottom to the top along the sensitivity line of renewable resources. The SI gradually increases to SI > 1.

Treatment IIIb (IS = 2.31) develops along the first path; the renewable resources of the system will contribute less and less to the treatment system. With a decrease in the proportion of local renewable resources, such as the phosphorus input generated by Patarcocha Lake, the demand for non-renewable resources such as acidic water increases, and the pressure on the environment increases. Since it is constrained by limited local renewable resources for a specific period of time and a reduced overutilization of local non-renewable resources, the sustainability of the system’s development is weakened.

The second development path is on Treatment I, Treatment II, and Treatment IIIa, where the current proportion of non-renewable resources and socio-economic emergy are used as inputs while improving the emergy proportion of renewable resources. Along with this development, it is necessary to improve the capacity and social and economic emergy contributions, and the utilization rates of renewable resources of these treatments increase synchronously. With a decrease in the proportion of non-renewable resources, the ELR decreases, the emergy production rate of the treatment process increases, and the sustainability of system development increases. Obviously, the second development path is the sustainable development mode to be chosen.

5. Conclusions

In this paper, sustainability is calculated in different scenarios of co-treatment systems between urban wastewater and acidic water, and it is expressed in terms of a ternary emergy diagram. It is shown that, of the four treatment scenarios proposed, Treatment
I (primary settling tank), Treatment II (primary settling tank + artificial wetland), and Treatment IIIa (primary settling tank + electrocoagulator) are sustainable in the long term, while Treatment IIIb is sustainable in the medium term.

The sustainability indices obtained through the ternary diagram highlight that the amount of volumetric mixing between acidic and urban wastewater plays the most important role in emergy flows and sustainability. The compared treatments have a low environmental load of ELR < 2; this is due to the fact that using wastewater as a renewable and non-renewable natural resource does not generate stress in natural systems. The combination of these wastewaters generates a great contribution to the system as a natural resource and increases its emergy contribution (EYR > 1). All four treatment scenarios present an EIR of < 1, confirming that the amount of emergy imported to the system is less than the renewable and non-renewable energies used. None of the four treatments present an SI < 1; Treatment IIIb has an IS range of 1 < SI < 3, causing it to be considered as a sustainable system in the short term, while Treatments I, II, and III a have an IS of > 5, so the system has long-term sustainability.

The co-treatment of wastewater is a complex and dynamic process with a variety of types of input and output units. When using the emergy analysis method to analyze the benefit for the development of a co-treatment system for the wastewater of the Pasco-Peru region, the input and output values of the entire system must be considered, as well as the distribution of emergy among the treatment factors during operation. The ternary diagram of the emergy analysis directly reflects the allocation of system resources. With the help of the auxiliary lines of the ternary emergy diagram analysis, the relationship between the emergy utilization rate and system indicators can be analyzed, and the sustainability of future wastewater co-treatment systems can be comprehensively evaluated.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16072609/s1, Figure S1: General scheme of Treatment I; Figure S2: General scheme of Treatment II. Figure S3: General scheme of Treatment IIIa and Treatment IIIb. Table S1: Renewable emergy flows. Table S2: Non-renewable emergy flows. Table S3: Imported emergy flows.

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