Circular Economy Biorefinery for Producing Biofertilizers, Biogas, and Bioenergy from Biomass: Conceptual Design, Process Characterization, and Thermo-Economic Assessment

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Abstract– This paper proposes the conceptual design and start-up of circular economy biorefineries (BUB) based on anaerobic biodigesters to process municipal organic matter (MOM) and livestock manure. The system produces biofertilizers to support organic agriculture and biogas as a renewable fuel for electricity generation in adapted internal combustion engines, providing a sustainable pathway for waste valorization. The proposed circular economy framework promotes organic farming, rural reforestation, renewable fuel production, and local energy self-sufficiency, contributing to the energy transition and food sovereignty in vulnerable communities. A thermo-economic analysis shows strong financial viability, with high return on investment (ROI) and reduced dependence on fossil fuels. The results demonstrate the potential of this frugal innovation model to foster local economies, open new market opportunities, and advance sustainable development through scalable and replicable biorefineries adapted to regional conditions.

Key words: Biofertilizer Production, Biogas Digestate, Organic Waste Valorization, Circular Biorefinery

I. INTRODUCTION

According to the National Council of Economic and Social Policy (CONPES) 4129 [1], Colombia has re-primarized its productive activity, showing strong dependence on the energy and mining sector and a parallel process of deindustrialization, reflected in weak productivity and low value-added generation. This situation is aggravated by the decline of the industrial sector, the incipient development of innovation-based services, and global pressures such as biodiversity loss and climate change. Among the structural causes are the limited productive linkages between sectors, low integration into global value chains, and insufficient transfer of knowledge and technology from universities. In response, CONPES [1] proposes a reindustrialization policy in which the government shifts from a facilitator role to that of a production organizer, guiding investment through intersectoral strategies. The plan establishes priorities such as a fair energy transition, agribusiness focused on food sovereignty, and reindustrialization grounded in sustainability and inclusiveness. This framework seeks to strengthen micro, small, and medium-sized enterprises, promote circular economy practices, stimulate renewable energy and bioeconomy initiatives, and foster green businesses that contribute to territorial development and climate change management.

Circular Economy (CE) seeks to eliminate the concept of waste by promoting comprehensive resource use and reuse, emphasizing both financial returns and resource recovery. Its framework is based on seven principles: upcycling, collaborative economy, circular repair, remanufacturing, functional economy, ecological design, and the implementation of BUB plants. These plants enable the large-scale valorization of organic material, offering an effective pathway to produce diverse bioproducts and bioenergy [2,3]. Unlike conventional oil refineries, BUB systems generate outputs with significantly lower environmental impacts, including biofertilizers, biogas, syngas, biodiesel, bioethanol, biopolymers, bio-oil, bioplastics, and biochar [4–6]. Broadly, BUB plants fall into two categories: thermochemical systems, such as gasification and pyrolysis, and biochemical systems, such as anaerobic digestion, which rely on microbial or enzymatic activity to convert biomass into valuable compounds [7–9].

The core of the biorefining process lies in efficiently transforming diverse biomass feedstocks into fuels, chemicals, and value-added materials through microbial or enzymatic activity. In this context, cell factories and molecular machines play a pivotal role in supporting the operation and scalability of BUB technologies. Anaerobic digestion technology enables nutrient recovery, with the digestate serving as an effective biofertilizer. This process provides an integrated approach to recovering both energy and nutrients from organic biomass sources [10,11]. BUB plants are essential for advancing integrated industrial production and fostering economic development. They offer solutions for waste management, energy generation, and value creation by transforming waste into cyclical, restorative, and regenerative processes that support a sustainable and inclusive economy [12–14], thereby reducing the environmental burden of the prevailing linear consumption model.

Despite the advantages offered by CE models, several critical perspectives highlight fundamental limitations. Critics argue that CE lacks a well-defined theoretical foundation and presents diffuse conceptual boundaries, while its implementation faces significant structural barriers. The CE framework is often shaped by a conceptual agenda primarily dominated by technical and economic considerations, which results in ambiguous contributions to sustainability [15]. Moreover, CE is frequently promoted without fully addressing the need for systemic change. Existing definitions rarely establish clear connections between the CE concept and broader sustainable development frameworks. While CE emphasizes economic performance alongside environmental quality, its implications for social equity—particularly regarding future generations—are often underdeveloped or superficially addressed [16]. These critiques suggest that some of the structural and conceptual dimensions of CE require deeper investigation and clarification to ensure that the model truly supports comprehensive and inclusive sustainability.

The central research question addressed in this study is: *Can each municipality develop biorefineries to produce biofertilizers, biogas, and electricity from locally available biomass, thereby promoting organic agriculture and decentralized energy generation to enhance local economic development and productivity?*

This research provides fundamental information required to plan individual municipal projects aimed at improving solid waste management systems. The proposed model is based on the use of anaerobic biodigestion to produce biogas for electricity generation and biofertilizers to support reforestation and the expansion of organic agriculture. The primary objective is to foster and facilitate the technological transfer necessary for the implementation and scaling of BUB plants. By promoting widespread biogas production, this approach seeks to support the generation of renewable electrical bioenergy and the use of biofertilizers to strengthen food sovereignty and sustainable land restoration at the municipal and departmental levels. The research follows an explanatory scope, as it seeks to analyze the causes and potential impacts of implementing BUB plants for organic matter conversion into biogas and biofertilizers. The methodology is descriptive, as it proposes a technological solution that can be readily adopted to support the emergence of a new local economy—one that replaces fossil fuel dependency and reduces the use of agrochemicals in agricultural practices.

II. Circular economy model and background.

A. Circular Economy Model

A circular economy (CE) model was previously proposed [17], based on the source separation of municipal solid waste (MSW) into two distinct streams: MOM and municipal inorganic material (MIM). The MIM stream can be directed toward recycling, restoration, reuse, and remanufacturing processes to reduce the extraction and use of virgin natural resources. MOM is generated primarily from households, restaurants, supermarkets, and workplaces. As shown in Fig. 1, MOM must be collected separately from MIM and directed to BUB, where it undergoes a series of preparation and conversion stages. Initially, the organic material is crushed and mixed with water. The water used must have a neutral pH and be free from chlorine to avoid disrupting microbial activity. The prepared mixture is then fed into anaerobic biodigesters, where the absence of oxygen enables microorganisms to decompose the biodegradable matter. The anaerobic digestion process begins with hydrolysis, in which complex organic compounds are broken down into simpler sugars and amino acids. This is followed by acidogenesis and acetogenesis, where bacteria convert these products into volatile fatty acids—mainly acetic acid. Finally, in the methanogenesis stage, these intermediates are converted into biogas, primarily composed of CH_4, CO_2, and trace amounts of H_2S. Biogas can be used directly in spark-ignition (SI) engines to generate electricity, or as a feedstock to produce biohydrogen through various pathways. One route involves using biogas in an SI engine to generate electricity, which then powers electrolysis for green hydrogen production. Alternatively, chemical looping combustion offers a method for converting biogas into hydrogen with lower emissions.

Although these hydrogen production pathways are promising for enhancing the economic viability of BUB systems, their detailed analysis is beyond the scope of this paper. Nonetheless, the production of biohydrogen or green hydrogen from biogas represents a high-value output due to its application in industrial and technological processes, potentially improving the overall return on investment of the circular biorefinery model.

Biogas can be compressed to approximately 6 bar and utilized in SI engines specifically designed with high compression ratios (CR) and modified pistons that enhance turbulence intensity. This design increases the turbulent flame speed, reducing combustion duration and associated heat losses, thereby improving thermal efficiency and mechanical performance [18,19]. The exhaust gases generated from biogas combustion can be utilized in cogeneration systems, where thermal energy is recovered through heat exchangers to produce hot water or steam. Additionally, biogas can be used directly in specialized furnaces for thermal applications. A particularly eco-efficient alternative involves oxy-fuel combustion using biogas and exhaust gas recirculation (EGR) in industrial furnaces, allowing for the recovery of CO_2 via liquefaction systems. Liquefaction is a complex thermodynamic process that involves multiple compression and expansion stages to produce high-pressure, low-temperature conditions necessary for converting CO_2 gas into its liquid form. This CO_2 can be captured and reused or stored, offering an added environmental benefit and improving BUB plant performance.

The biofertilizers produced in BUB plants can be applied in organic agriculture, enhancing soil fertility and promoting the growth of trees and crops. This activity increases CO_2 absorption from the atmosphere and boosts oxygen production, contributing to climate mitigation.

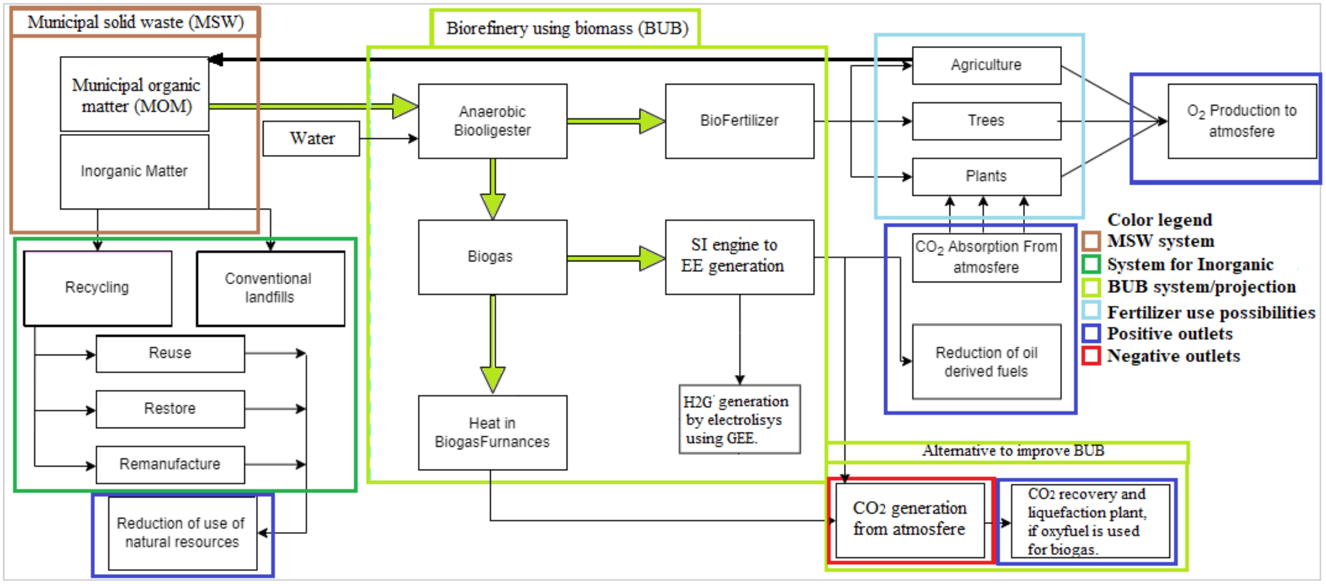

Fig. 1 Block diagram of the system components

As food production increases, more MOM is generated, which in turn can feed additional BUB plants—thus closing the circular loop. By promoting tree planting, organic food cultivation, and the substitution of fossil fuels with biogas, the proposed system enhances the carbon cycle, accelerates decarbonization of the atmosphere, and improves air quality. This integrated loop not only reduces greenhouse gas emissions but also fosters sustainable food systems. The continuous generation and treatment of MOM to produce biofertilizers and biogas form a self-reinforcing circular economy model that advances food sovereignty, organic agriculture, and climate resilience through atmospheric carbon removal.

B. Background

As part of the ongoing development of a CE model at the Technological University of Peru (UTP), a modular biodigestion system was constructed using recycled 1000-liter IBC tanks from the chemical industry, as illustrated in Fig 2. The system was tested and evaluated at the facilities of the National Institute of Agricultural Innovation (INIA) of the Ministry of Agriculture of Peru, located in La Molina, Lima. Experiments were conducted using manure from different farm animals, and the results revealed that the biofertilizer with the most favorable physicochemical properties was obtained using guinea pig manure, a domestic animal with broad productive importance in countries such as Peru, Bolivia, and Ecuador [17, 20–21].

Given that anaerobic biodigestion requires the optimized functioning of its four biological stages—hydrolysis, acidogenesis, acetogenesis, and methanogenesis—a novel 10 m³, three-stage biodigester was designed to enhance process performance and reduce substrate retention time. This system, shown in Fig. 3.

This biodigester is easily scalable up to 200 m³ and was engineered to improve microbial separation and cultivation conditions, particularly for the hydrolysis and methanogenesis phases. The biodigester is divided into three internal volumes:

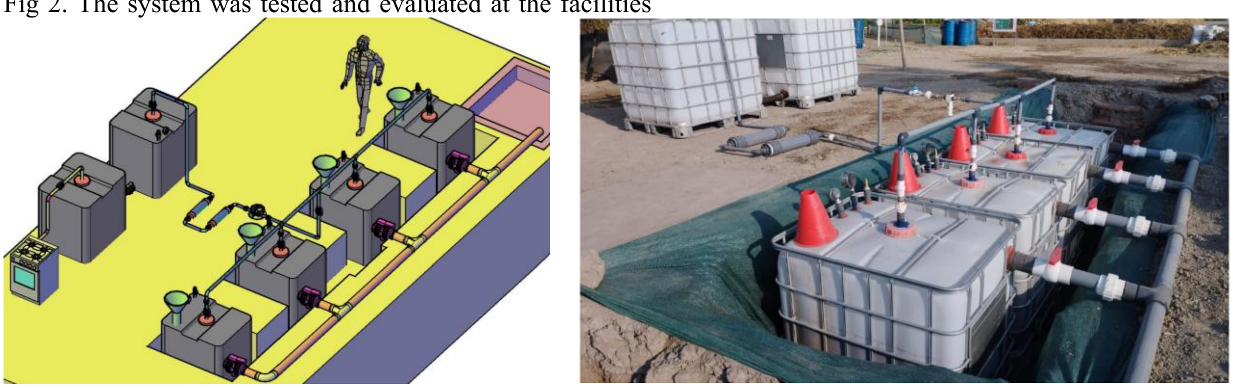

Fig. 2 Draft and photograph of a 4,000-liter biodigester using IBC tanks.

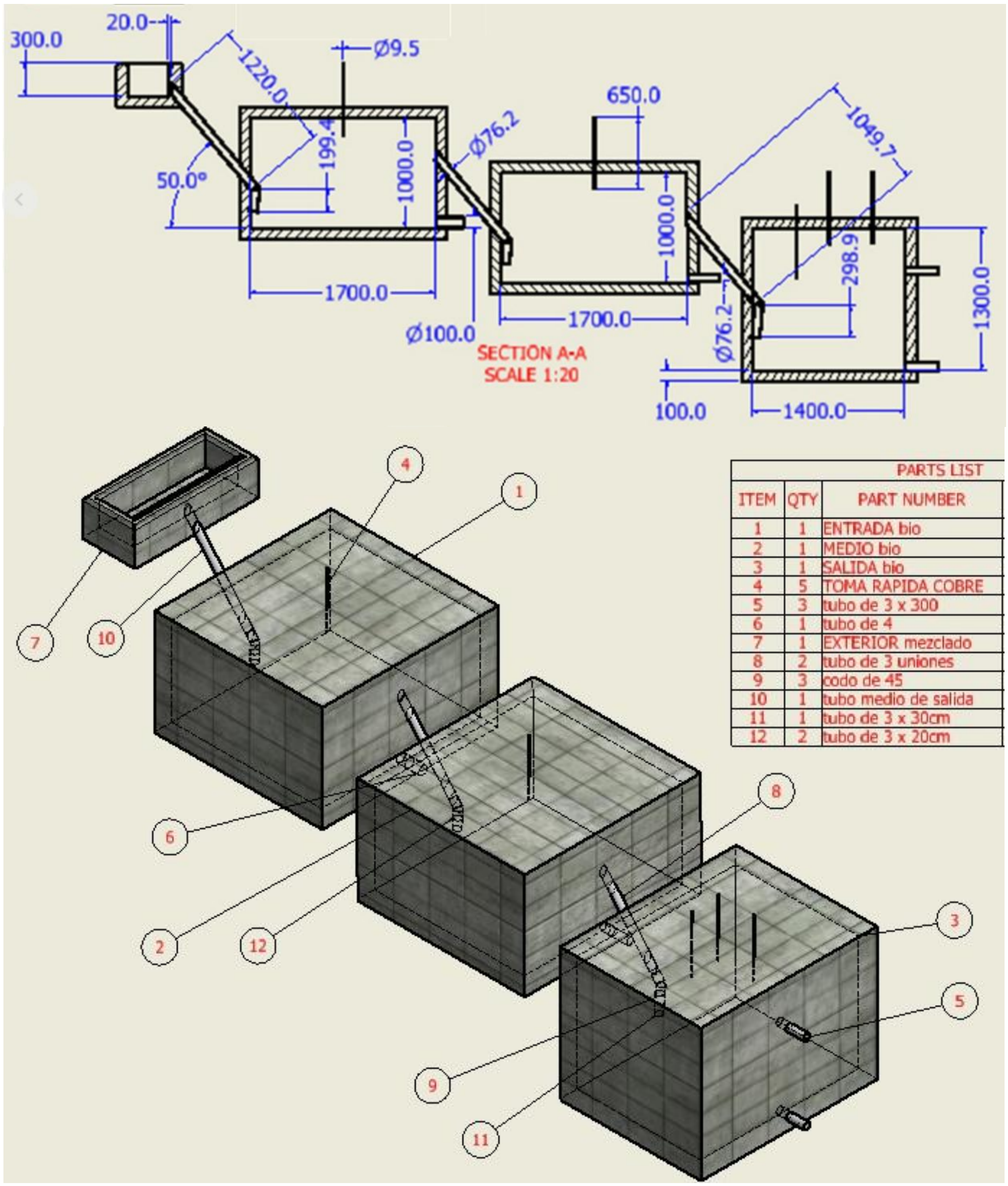

Fig. 3 Three-stage biodigester designed for 10 m^3 of total vol.

- The first chamber handles the hydrolysis process and is fed from an external 100-liter mixing tank where MOM is combined with water at a ratio of 2–3:1[23].
- The second chamber is designated for acidogenesis and acetogenesis.
- The third chamber facilitates methanogenesis and also acts as a biogas storage zone.

The separation of biological stages enables independent microbial activity under optimized conditions, improving the system's overall efficiency. The design leverages gravity, hydrostatic pressure, and density gradients to manage the internal flow of substrate and biol (liquid biofertilizer). Valves at the bottom of each tank allow for removal of solids for maintenance, while a side valve at 70% height in the third chamber collects the mature biofertilizer, also known as biol. The upper 30% of this volume serves as low-pressure biogas storage (30–50 mbar). Following collection, the biogas passes through a desulfurization system using iron particles, and is then stored in a buffer tank before being compressed and directed to a SI engine to generate green electricity. This experimental development serves as a scalable and replicable prototype for decentralized circular bioenergy systems and informs the broader conceptual design proposed in this study. The CE model and its analytical framework were previously formulated and published [17] as a case study focused on major South American economies, summarizing demographic and biomass generation data for the five most populated cities in each country. This approach established a foundational methodology to assess the feasibility and impact of implementing biorefinery systems based on local waste availability and energy needs. In parallel, several studies have explored the development of specialized internal combustion engines adapted for biogas. Notably, references [18, 19, 22] consolidate the most critical findings supporting the conversion of hybrid diesel engines to SI mode, incorporating high CR and piston geometries optimized for turbulence generation. These adaptations are specifically designed to match the physicochemical properties of biogas, leading to improved thermal efficiency, mechanical performance, and reduced environmental impact when compared to conventional fuels such as gasoline, natural gas, LPG, or diesel. Moreover, a conceptual design of highly efficient SI engines for biogas was introduced based on exergetic efficiency principles. This work demonstrated a clear correlation between recovered energy, exergetic performance, octane rating, and entropy generation in Otto cycle-based engines [22]. From this exergo-thermodynamic perspective, biogas was identified as the fuel with the highest energy quality, given its favorable combination of high octane number, chemical stability, and performance in high-CR SI engines operating near the knock limit. These findings form a solid scientific and technical foundation that supports the integration of advanced SI engine technology into the proposed CE model, maximizing the energy recovery potential of municipal biomass through locally adapted solutions.

C. *Scope of the investigation*

This investigation is framed within the technological transfer of knowledge and applied research to develop specialized biorefineries (BUBs) designed to produce biogas and biofertilizers using scalable anaerobic biodigestion systems—particularly the modular biodigester developed, which can be expanded up to 200 m³. While this specific biodigester is central to the research, the proposed CE model is compatible with other anaerobic digestion technologies, depending on local conditions and availability. Biogas generated through this process can be used in engines adapted for decentralized electricity generation, while the biofertilizers produced are intended to nurture organic crops, trees, and plants for reforestation, contributing to accelerated carbon cycling. These processes increase the absorption of atmospheric CO_2 and the production of oxygen, thereby improving air quality at both local and regional levels. The implementation of the CE model also fosters strategies to expand the generation of organic waste and biomass as raw materials, increasing the throughput and scalability of the cycle. This long-term vision aims to enable these systems to compete with oil-derived fuels in energy supply and productivity. The relevance of this proposal lies in its capacity to catalyze project development through technology transfer—targeting municipalities, companies, and the agro-industrial sector—where organic waste can be transformed into biofertilizers, biogas, thermal energy, and electricity. In addition, the model supports initiatives for land recovery and reforestation, particularly in infertile or desertified areas, and strongly promotes the expansion of organic agriculture. The biomass circular economy approach seeks to decarbonize the atmosphere and reduce the greenhouse effect that drives climate change. Moreover, the widespread construction and adoption of anaerobic biodigesters are positioned not only as a technological solution but also as a source of employment with significant economic potential. Biofertilizers are expected to compete with conventional chemical fertilizers such as urea, while contributing to a more diversified, resilient, and sustainable agricultural production chain—one that supports healthier food systems and greater profitability for producers. This research aims to contribute to bridging the knowledge and technology gap in Colombia and other Latin American countries with similar agricultural profiles, by providing practical, replicable solutions rooted in circular economy principles.

D. *Application of the Proposed Circular Economy Model*

This research builds upon a previously published CE model [17] to develop a quantitative analysis focused on determining the technical and economic requirements for producing enough biogas to power an engine capable of generating 10 kW of electrical energy. The main objective is to calculate and properly size a BUB plant that uses livestock manure and MOM as raw materials. The methodology begins with the assumption that high-efficiency SI engines optimized for biogas will be used. The sizing of the biodigesters is based on data from scientific literature and prior operational experience with anaerobic digestion systems. A critical parameter in this calculation is the organic matter-to-water ratio, which directly affects the reactor volume and residence time. For each input material (livestock manure and MOM), the analysis estimates: The required volume of raw material for sustained biogas production. The expected yield of biogas and biofertilizer. The dimensions and configuration of the biodigester modules. Subsequently, the model incorporates an economic feasibility study that includes: Initial investment requirements. Operating and maintenance costs. Potential cost savings from avoided fossil fuel consumption and fertilizer substitution. Finally, a thermo-economic analysis is conducted to calculate the internal rate of return (IRR) and evaluate the financial viability of the proposed BUB plant configuration under the CE model. Fig. 4 illustrates the step-by-step procedure for this analysis, including the material flows, sizing logic, and investment estimation.

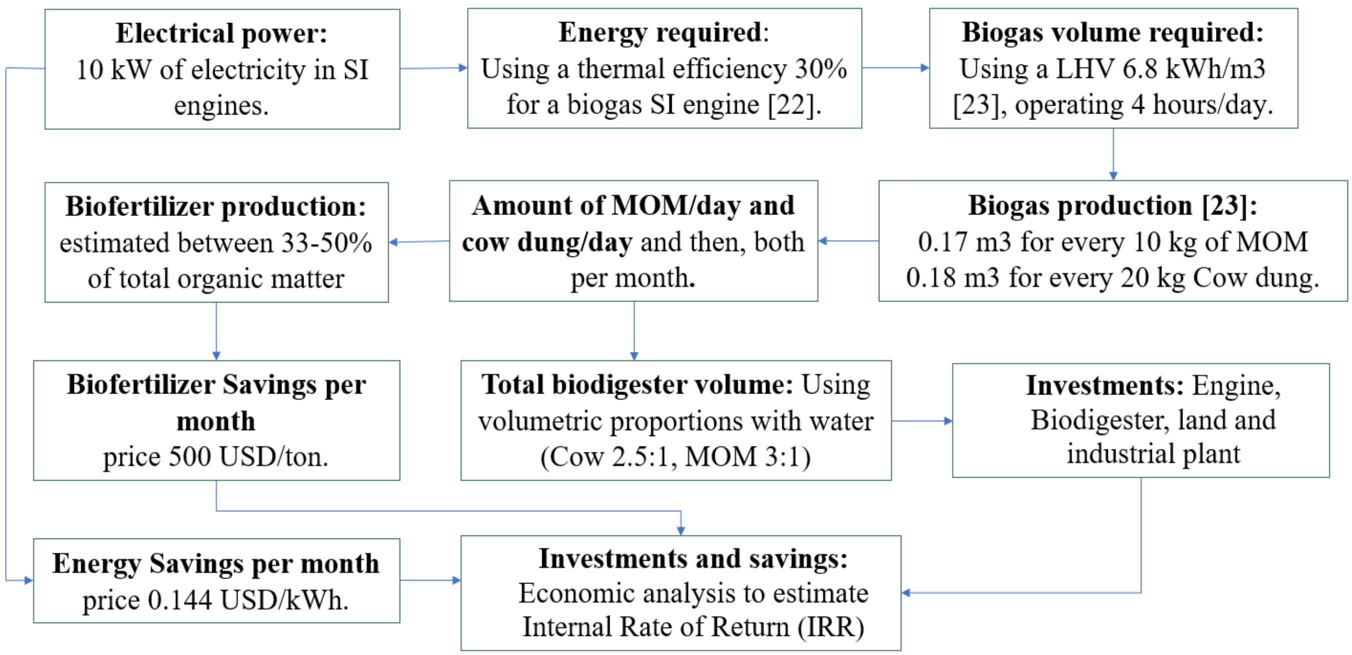

Fig. 4 Application of the proposed Circular Economy Model.

III. RESULTS FOR BUB PLANTS

A. Dimensioning of the BUB System

The following tables present the key specifications regarding biomass processing capacity for the proposed biorefinery unit. These include estimates of biofertilizer and biogas production, as well as the required investment in biodigesters, gas engines, land acquisition, and other essential infrastructure. Additionally, a thermo-economic analysis has been conducted to assess the investment feasibility. Based on the data in Table 1, to generate 10 kW of electrical power for 4 hours per day, a monthly production of 1,200 kWh is required. Assuming an average thermal-to-electric efficiency of 30% for the SI biogas engine, it is estimated that approximately 20 m³ of biogas per day must be produced to meet the electrical demand.

Table 1 Main information on the generation capacity in the engine.

Characteristic	Units	value
Engine output power	kW	10
Thermal efficiency	%	30
Energy required	kW	33.3
Operation Hours	h/day	4
Energy required per day	kW*h/day	133
LHV biogas	kW*h/m³	6.8
Biogas volumen	m³ /day	19.6
Energy produced per month	kW*h/month	1,200

Table 2 presents the comparative analysis of two case studies, each involving a biodigester designed to produce 20 m³ of biogas per day. The analysis considers a lower heating value (LHV) of 6.8 kWh/m³, corresponding to a typical biogas composition of 60% CH_4 and 40% CO_2. The two feedstock types analyzed are municipal organic matter (MOM) and cow dung. For each case, the required amount of biomass to be processed monthly is estimated based on the specific biogas yield and the appropriate biomass-to-water ratio [23]. The volumetric capacity of the biodigesters is then calculated accordingly. Results show that the biodigester required for cow dung must be larger than the one for MOM, as MOM generates a higher volume of biogas per unit of organic mass compared to cow dung.

Table 2 Main information on capacity specifications.

Characteristic	Units	Value
Biogas volume	m³ /day	19.61
Biogas from MOM	m³	0.17
Amount of slurry MOM	kg	10
Biogas from cow	m³	0.18
Amount of slurry cow dung	Kg	20
Amount of MOM/day	kg/day	1,153
Amount of slurry cow/day	kg/day	2,179
Amount of MOM/month	tons/month	35
Amount of slurry cow/month	tons/month	65
Volume of MOM/month	m³ /month	38
Volume of slurry cow/month	m³ /month	73
Biodigester volume MOM	m³	115
Biodigester volume slurry COW	m³	182

B. Thermo-Economic Analysis of BUB Plants

Table 3 summarizes the estimated investment requirements for a BUB plant designed to operate with either of the two biomass types. Both configurations utilize the same proposed internal combustion engine: a converted Lister Petter TR2 diesel engine, adapted for SI, with two cylinders, 1550 cc, and a CR of 15.5:1. Referential costs were estimated for the biodigester, land acquisition, and basic industrial infrastructure, including machinery such as crushers and dryers. These estimates are based on prices in intermediate-sized cities in Colombia, taking into account average costs of materials, labor, and equipment. In larger urban centers, costs may increase by approximately 20%, while in rural areas or small towns, they may decrease by up to 10% due to lower cost of living and construction. The engine cost remains the same in both cases and is typically sourced from suppliers located in major cities. However, due to differences in biodigester volume, and required infrastructure, cow dung-based biorefineries are estimated to require approximately 9% more investment than those designed for MOM.

Table 3 Investments required (USD) per BUB plant.

Investments (USD)	MOM	Slurry Cow
Engine	13,000	13,000
Biodigester	25,000	30,000
Land	25,000	25,000
Industrial Plant	15,000	17,000
Total investments	78,000	85,000

Table 4 presents the cost–benefit analysis of the BUB system based on the estimated monthly production of electrical energy using biogas, along with the generation of biofertilizers. The economic value of the biofertilizer is based on comparable commercial products; however, a conservative unit price of USD 500 per ton is used for the projection, despite estimates suggesting a potential market price of up to USD 800/ton, depending on location and demand. Operating costs are estimated as 100% of the cost of electricity generation plus 20% of the revenue value of the biofertilizer. This assumption reflects labor, maintenance, and auxiliary energy expenses. The net monthly savings were calculated by subtracting operating costs from the combined economic value of electricity and biofertilizer production. The results highlight that biofertilizer production represents the most significant economic contribution of the system. This is particularly relevant in regions where chemical and organic fertilizers are limited, costly, or poorly distributed, often becoming the main financial burden for small-scale food producers. It is expected that the availability of high-quality, locally produced biofertilizer will contribute to a paradigm shift in sustainable food production. Preliminary laboratory and field tests conducted by INIA (National Institute for Agricultural Innovation) in Lima have demonstrated excellent results, especially in the case of corn cultivation, validating the agronomic potential of the product.

Table 4 Analysis of costs and savings of the system.

Savings	unit	MOM	Slurry Cow
Amount of biofertilizer	Tons/month	11.5	21.8
Ton price biofertilizer	USD/ton	500	500
Savings by biofertilizer	USD/month	5,767	10,893
Energy produced	kW*h/month	1,200	1,200
Cost electrical energy	USD/kWh	0.144	0.144
Savings by energy	USD/month	173	173
Cost of operation	USD/month	1,326	2,351
Net savings	USD/month	4,613	8,714

Table 5 presents the investment return analysis over a 3-year horizon, aligned with the typical term of municipal and departmental governments in Colombia—key stakeholders for the potential implementation of this type of project. The initial capital investment (Year 0) is estimated at USD 78,000 for the system utilizing municipal organic matter (MOM) and USD 85,000 for the system based on cow dung. The higher investment for the latter is due to the larger biodigester volume required to achieve the same daily biogas production. Despite the higher upfront cost, the monthly and annual net savings are greater for the cow dung-based system, mainly due to the larger volume of biofertilizer produced, which contributes significantly to the project's profitability. As a result, the internal rate of return (IRR) is estimated at 42% for cow dung and 94% for MOM, reflecting the advantage of economies of scale in systems processing larger volumes of biomass. This project represents an innovative energy and agricultural solution, with attractive returns within a short time frame. It offers a new dynamic for farmers, local governments, and markets, while fostering the development of a green economy in rural areas. Furthermore, it directly addresses strategic goals outlined in CONPES 4129, which calls for innovation-driven development to stimulate economic growth, enhance technological sovereignty, and reduce dependency on imported chemical inputs.

Table 5 Investment return analysis (3-year horizon)

IRR	Unit	MOM	Slurry Cow
Year 0 Investments	USD	- 78,000	- 85,000
Year 1 savings	USD	44,291	83,660
Year 2 savings	USD	55,363	104,575
Year 3 savings	USD	55,363	104,575
IRR	%	42%	94%

C. Construction and Start-Up of the Project

The implementation timeline for the biorefinery project is estimated at approximately nine months, which includes all phases from construction to full operational capacity: Construction phase: 4 months; Start-up and testing phase: 1 month and 10 days; Biodigester maturation period: 4 months (required to reach stable biogas and biofertilizer production). This timeline reflects the typical ramp-up curve observed in anaerobic digestion systems, where microbial stabilization and organic matter degradation must reach optimal levels before achieving peak productivity. Table 6 presents the distribution of the volume of tanks and subsystems, including biodigesters, gas storage domes, and digestate reservoirs. In all configurations, the final stage tank has a larger volume, providing additional storage capacity for biogas accumulation, ensuring system continuity and buffering for variable demand.

Table 6 Distribution of volumes for each type of biodigester.

Biodigester distribution	unit	MOM	Slurry Cow
Volume tank 1	m^3	38	60
Volume tank 2	m^3	38	60
Volume tank 3	m^3	39	62

The feeding process of the multi-chamber biodigester follows a staged loading protocol designed to sequentially activate the biological phases of anaerobic digestion: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The procedure spans over one month, with full stabilization occurring by the fifth month. The step-by-step operation is described below:

1. Day 0 – Initial Feeding for Hydrolysis Phase. The first chamber is filled completely to initiate hydrolysis:
   - MOM-based system: 11 m³ of MOM + 27 m³ of water
   - Cow dung system: 15 m³ of cow dung + 45 m³ of water
2. Day 8 – First Transfer to Acidogenesis Phase. Half of the hydrolyzed substrate is transferred to the second chamber (acidogenesis and acetogenesis), while the first chamber is reloaded with fresh substrate:
   - MOM: 5.5 m³ + 13.5 m³ water
   - Cow dung: 7.5 m³ + 22.5 m³ water
3. Day 15 – Second Transfer to Acidogenesis. The remaining hydrolyzed substrate from chamber one is transferred to chamber two, completing its volume. Chamber one is again refilled as in the previous step.
4. Day 23 – Transfer to Methanogenesis Phase. Half of the acidogenic substrate is moved to the third chamber (methanogenesis). Chamber two is refilled with hydrolyzed substrate from chamber one, which is also reloaded accordingly.
5. Day 30 – First Biogas Ignition Test. Transfers continue: from chamber two to three, one to two, and fresh feeding into chamber one. The first biogas ignition test is performed at this stage.
6. Days 37–40 – Initial Extraction Phase. Biogas and biofertilizer are extracted from chamber three. Transfers follow the same pattern (2→3, 1→2), and daily feeding of chamber one begins:
   - MOM: 1.3 m³/day + 3 m³ of water
   - Cow dung: 2.4 m³/day + 7 m³ of water
7. Month 5 – Full Maturation. The system reaches maximum biogas and biofertilizer productivity. This is the ideal time to conduct physicochemical analyses of both products for performance validation and quality control.

D. Greenhouse Gas Equivalents and Environmental Impact

To quantify the environmental benefits of the proposed biorefinery, the Greenhouse Gas Equivalency Calculator from the United States Environmental Protection Agency (EPA) [24] was used. Based on a projected production of 1,200 kWh/month of renewable electricity from biogas, the system would offset approximately 0.838 metric tons of CO_2 emissions per month. The EPA tool translates this abstract carbon footprint into more tangible equivalences, highlighting the system's potential to reduce reliance on fossil fuels and support climate mitigation. The monthly production of 1,200 kWh of bioenergy corresponds to: 82.3 gallons of diesel not burned; 94.3 gallons of gasoline avoided; 939 pounds of coal not consumed; 1.9 barrels of oil not used; Carbon sequestration equivalent to 14 urban trees grown over ten years. These figures demonstrate that the adoption of BUB plants for decentralized energy generation and sustainable agriculture can significantly contribute to local climate goals, promote low-carbon technologies, and provide co-benefits in both rural and peri-urban communities.

E. Descriptive Analysis: Biol as an Example of Biofertilizer Production in a Biorefinery Using Guinea Pig Manure

The Table 7 **presents a d**escriptive analysis of biol versus standard range. The biol sample COD1 was produced using guinea pig manure as input in a biodigestion system operating in series, serving as a representative case of a small-scale biorefinery focused on circular economy practices.

Table 7 Descriptive Analysis: Biol versus standard range

Parameter	Biol (COD1)	Standard Range
pH	7.96	6.0 – 8.5
E.C. (dS/m)	14.09	< 10
Total Solids (g/L)	141.61	10 – 50
Soluble Organic Matter (g/L)	98.71	5 – 30
Total Nitrogen (mg/L)	3737.51	1000 – 2500
Total Phosphorus (mg/L)	642.21	100 – 500
Total Potassium (mg/L)	3200	1500 – 3000
Calcium (mg/L)	1473.33	150 – 400
Magnesium (mg/L)	600	50 – 200
Sodium (mg/L)	900	< 100
Copper (mg/L)	5.83	0.2 – 1.0
Manganese (mg/L)	25	0.5 – 5.0
Iron (mg/L)	298	2.0 – 10.0
Zinc (mg/L)	4.32	1.0 – 5.0
Boron (mg/L)	3.25	0.5 – 2.0

This liquid biofertilizer shows a nutrient profile that exceeds typical reference standards in nearly every parameter. With an electrical conductivity (EC) of 14.09 dS/m, the sample indicates a high concentration of soluble salts—beneficial for nutrient density but requiring dilution to avoid soil salinization. Total nitrogen (3737.5 mg/L), phosphorus (642.2 mg/L), and potassium (3200 mg/L) are significantly above common biofertilizer norms, suggesting strong fertilizing potential, especially during vegetative and flowering stages. Micronutrients such as calcium (1473.3 mg/L), magnesium (600 mg/L), and iron (298 mg/L) also exceed conventional thresholds. While this can enhance plant development, especially in deficient soils, it also requires careful management to prevent toxicity. Trace elements like zinc (4.39 mg/L), manganese (25 mg/L), and boron (3.25 mg/L) are also present in higher-than-standard levels, offering agronomic benefits if properly monitored.

COD1 biol, produced from guinea pig manure in a biorefinery process, has high levels of macro- and micronutrients, including nitrogen (960 ppm), potassium (1830 ppm) and trace elements. Its high electrical conductivity (14.09 dS/m) requires dilution to prevent phytotoxicity and soil salinity issues.

- Dilution: Use 1:10 (biol:water) for foliar application or fertigation in sensitive crops; 1:5 may be tested in tolerant crops or organic soils.
- Frequency: Apply every 15–20 days during vegetative growth; avoid during flowering unless field-tested.
- Methods: Suitable for soil drench, fertigation, or foliar spray with proper dilution.
- Target crops: Effective in vegetables, fruit trees, and tubers, supporting growth and fruiting stages.
- Soils: Recommend prior soil testing; especially useful in degraded soils with micronutrient deficiencies.

IV. Future Work and Perspectives: Towards an Integrated BUB System with Green Hydrogen and Advanced Oxyfuel Combustion

As a future development of the BUB system proposed in this paper, a more technologically advanced version of the biorefinery is envisioned, integrating green hydrogen production, oxyfuel combustion with high levels of exhaust gas recirculation (EGR), and closed-loop circular economy principles aimed at maximizing exergy efficiency and minimizing environmental impact. In this enhanced model, the biogas produced from municipal organic matter and livestock waste is used in SI engines adapted for oxyfuel operation, where oxygen replaces atmospheric air as the xidant. A high proportion of EGR—primarily CO_2 and water vapor—is reintroduced into the combustion chamber. These high EGR levels act as effective thermal moderators, enabling controlled combustion temperatures comparable to air-based systems, and maintaining similar knock resistance, even under higher CR. Electricity generated by the engine can feed an electrolysis unit, producing green hydrogen and oxygen. While hydrogen may be used for other energy or industrial applications, the oxygen byproduct can be reused in the engine's oxyfuel combustion process, significantly reducing the need for external oxygen supply and increasing system autonomy. An additional benefit of this configuration is the nearly pure CO_2 exhaust stream, resulting from the absence of nitrogen in the oxidant. This facilitates direct CO_2 capture and reuse, whether for agricultural applications, synthetic fuel production, or long-term storage. The system could thus potentially operate as carbon-neutral or even carbon-negative, depending on the final use of the captured CO_2.

Moreover, the continued production and application of biofertilizers in organic agriculture and reforestation programs further contributes to atmospheric CO_2 absorption and soil regeneration. When combined, these elements result in a highly efficient and integrated biorefinery model capable of closing material and energy cycles while fostering local development and environmental sustainability. This advanced concept—BUB + Green H_2 + Oxyfuel + EGR—represents a long-term evolution of the current BUB model presented in this study, which is based on traditional air-fueled combustion without EGR. It reflects a natural progression toward more sophisticated, efficient, and self-sustaining energy systems capable of addressing both local and global sustainability challenges.

V. Operational, Economic, and Social Considerations

Beyond the demonstrated technical and economic feasibility, several complementary factors must be considered for successful deployment of BUB plants. **Operation and maintenance.** Rural contexts may face challenges such as irregular feedstock supply, water limitations, or lack of technical expertise. Modular designs, community training, and monitoring protocols for pH, solids, and gas composition, combined with preventive maintenance, can ensure reliability. **Economic sensitivity.** Financial performance is sensitive to changes in market conditions. A ±20% variation in biofertilizer price or engine efficiency significantly affects IRR and payback time, highlighting the need for local market assessments and flexible financing mechanisms. **Social impact.** Community adoption is essential. BUB systems can create green jobs, reduce dependency on chemical fertilizers, and strengthen local associations, directly contributing to food sovereignty and rural development. **Decision framework.** Municipalities should evaluate suitability using technical (feedstock and water availability), economic (ROI, savings), and social (number of beneficiaries) indicators. In summary, by integrating operational management, sensitivity analysis, social impact, and a decision-making framework, the BUB model is reinforced as a practical and replicable frugal innovation strategy for Latin America.

VI. Conclusions

This study provides the essential technical and economic information required to design and implement modular biorefinery units that process biomass—particularly MOM and livestock waste—through anaerobic digestion. The proposed system enables the generation of biogas for renewable electricity and the production of biofertilizers, contributing simultaneously to sustainable waste management, organic agriculture, and territorial food sovereignty. Although the analysis has been conducted within the Colombian context, the methodology and findings are scalable and adaptable to other Latin American countries facing similar challenges in MSW treatment, rural electrification, and fertilizer access.

The main conclusions are summarized as follows:

- Energy Viability and Biogas Requirements. To generate 10 kW of electrical energy for 4 hours daily (1,200 kWh/month), a BUB plant must produce 20 m^3 of biogas per day with a typical composition of 60% methane and 40% carbon dioxide, confirming the technical viability of decentralized bioenergy systems based on anaerobic digestion. Comparative Investment and Efficiency Although cow dung-based biorefineries require 9% more initial investment than those using MOM, they offer greater long-term savings and higher biofertilizer yield, due to the larger volume of biomass processed and the economy of scale achieved.

- Circular Bioeconomy and Technological Innovation. The proposed BUB system promotes an innovative model of circular bioeconomy, integrating waste-to-energy and organic fertilizer production. It fosters food sovereignty, reforestation, and sustainable agriculture, especially in rural and peri-urban territories of Latin America.
- Economic Feasibility and IRR. Both MOM and cow dung systems demonstrate strong economic feasibility, achieving a favorable IRR within 3 years—42% for MOM and 94% for cow dung—making them highly attractive for municipal and departmental governments as scalable public investments.
- Climate and Environmental Benefits. Each BUB plant can offset approximately 0.838 metric tons of CO_2 emissions per month, equivalent to avoiding the use of 94.3 gallons of gasoline, 939 pounds of coal, or 1.9 barrels of oil. This positions the technology as a low-carbon, climate-resilient solution aligned with regional and global sustainability goals.
- COD1 represents a concentrated and nutrient-rich biol, showcasing the potential of guinea pig manure as input in decentralized biorefinery models. Despite exceeding several standard parameters, it holds promise for use in sustainable agriculture, provided that application is controlled and tailored to crop and soil needs. Further research is recommended to define optimal dilution ratios and field performance.

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