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Powering pineapple industry with pineapple residues - A circular bioenergy strategy for Costa Rica

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ABSTRACT

Costa Rica's pineapple industry produces millions of tons of agricultural residues annually, with pineapple leaves often managed through environmentally harmful open-field burning. This study develops a novel and scalable circular bioenergy strategy that transforms pineapple leaves into compressed renewable natural gas (CRNG) and renewable power, while supporting pineapple cold-chain logistics. The integrated system co-locates anaerobic digestion (AD), CRNG fueling infrastructure, and refrigerated fruit storage at strategically optimized depot sites. Using geographic information systems (GIS), multi-objective optimization (MOO), process modeling and simulation to obtain mass and energy balances, and environmental impact evaluation, a systems-level analysis was conducted across five production sections. The system processes approximately 7.52 million metric tons of pineapple leaves annually, producing 39,530 metric tons of CRNG, 688,504 metric tons of dry pulp, and 5.59 million metric tons of digestate. Energy recovery from CRNG and pulp combustion totals 15.34 billion MJ/year, resulting in a net energy surplus of 10.66 billion MJ/year, enabling the system to fully power its operations and supply additional energy for external use. The environmental impact analysis suggests substantial environmental benefits compared to open burning, including the reduction of 81,211 metric tons of CO_2-equivalent emissions, elimination of 14,927 metric tons of particulate matter, and prevention of 2,316 metric tons of acidifying gases and 70,619 metric tons of smog-forming emissions annually, based on the processing of 7.52 million metric tons of pineapple leaves. This integrated approach not only improves energy resilience and rural sustainability but also serves as a replicable model for tropical agricultural systems seeking technically viable, logistically optimized, and environmentally superior solutions for large-scale residue management.

1. Introduction

Costa Rica is one of the world's largest producers and exporters of pineapples, with the industry playing a vital role in the country's agricultural economy. The tropical climate and fertile soils support year-round cultivation. There are over 65,000 ha of land devoted to pineapple farming and generating significant employment in rural Costa Rica [1]. Pineapple exports contribute substantially to the national GDP and foreign exchange earnings [2]. However, the rapid expansion of the pineapple sector has raised growing environmental and logistical concerns [3], particularly related to the management of agricultural residues and the reliance on fossil fuels for post-harvest operations and transportation. The most significant residues of pineapple cultivation are pineapple plants (leaves are the main part of the plant), which are left in the fields in large quantities after two-cycle harvest [4]. These residues are often burned or left to decompose, posing environmental issues such as air pollution, greenhouse gas (GHG) emissions, and nutrient runoff [5]. Similar challenges associated with residue accumulation and open-field burning have been reported across a range of tropical and subtropical cropping systems, where high biomass productivity coincides with limited on-site utilization pathways. At the same time, the decentralized nature of pineapple plantations, dispersed across remote rural areas, creates logistical inefficiencies and high fuel demand for harvesting and transporting pineapples from farms to depots

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or export terminals. These operational activities are typically powered by diesel, further exacerbating the carbon footprint of the supply chain [6]. As Costa Rica advances its commitment to carbon neutrality and environmental sustainability [7], there is a pressing need to transform agricultural waste into valuable resources. Addressing both the issue of biomass residue management and fossil fuel dependence in the pineapple supply chain presents a unique opportunity for innovation in sustainable agriculture and rural development.

The concept of a circular bioeconomy offers a promising framework for transforming agricultural systems into more sustainable, resilient, and resource-efficient models [8,39,40]. By converting biomass residues into feedstocks for energy and bio-based products, circular bioeconomy strategies facilitate waste reduction [4] nutrient recycling [9] and localized energy generation [10] Such strategies contribute to improved environmental performance while supporting economic diversification and enhancing energy self-sufficiency in rural communities. Within this context, bioenergy solutions that utilize locally available agricultural residues can play a critical role in reducing fossil fuel use, lowering emissions, and enhance rural energy security. Nevertheless, the effectiveness of circular bioenergy systems depends strongly on how feedstock collection, infrastructure siting, and energy utilization are coordinated across geographically distributed production landscapes.

Among the available bioenergy technologies, the production of renewable natural gas (RNG) through anaerobic digestion (AD) of agricultural residues stands out as a scalable and technically mature approach [11]. RNG, primarily composed of methane, can be upgraded and compressed to meet transportation fuel standards, serving as a clean and renewable alternative to conventional fossil fuels. Compared to gasoline and diesel, RNG offers significant GHG reduction benefits, and can contribute to closing the loop in agricultural production by powering harvest and post-harvest activities using energy derived from on-farm residues. In the case of Costa Rica's pineapple industry, utilizing pineapple leaves, a nutrient-rich residue, as feedstock for RNG production presents a unique opportunity to establish a self-sustaining transport system [12]. When combined with energy optimization and strategic depot siting [13], this approach could support a circular and low-carbon supply chain model for tropical agriculture.

Despite the promising potential of circular bioenergy strategies, effective implementation requires an integrated assessment that considers multiple dimensions, including biomass availability, spatial logistics, system efficiency, and environmental performance. A combination of analytical tools is often essential to support data-driven, site-specific decision-making for decentralized energy systems. In this context, Geographic Information Systems (GIS) can provide spatial insight into the precise geolocation of biomass distribution, as demonstrated in regional biogas supply analyses [14], while also supporting the assessment of infrastructure and accessibility constraints in resource management applications [15]; moreover, GIS-based models enable the identification of spatial patterns and availability of biomass resources, forming a basis for evaluating supply potential and logistical feasibility [16]. Multi-objective optimization (MOO) is particularly valuable in addressing the inherently conflicting goals that arise in transportation and infrastructure planning [17]. For example, minimizing feedstock collection distances may conflict with the need for proximity to road networks or fuel distribution points [18]. By identifying trade-offs among competing objectives, this approach enables the selection of depot or facility locations that reflect balanced logistical and operational priorities [19]. Environmental impact evaluation offers a structured framework for quantifying environmental impacts across the system, such as GHG emissions, air pollution, and fossil fuel displacement [13], allowing for a comprehensive comparison between circular bioenergy strategies and conventional practices [20]. When applied in an integrated manner, these complementary tools enable a holistic systems-level assessment that links spatial planning decisions with energy performance and environmental outcomes, which is essential for designing scalable and policy-relevant bioenergy systems.

This study evaluates the technical, spatial, and environmental feasibility of utilizing pineapple leaves for the production of RNG to power pineapple transport operations in Costa Rica (Fig. 1). The approach integrates GIS-based mapping of pineapple cultivation and residue availability with multi-objective optimization to identify optimal locations for decentralized bioenergy depots and fuel distribution points. A comprehensive mass and energy balance is developed to characterize system performance across key unit operations. In addition, an environmental impact analysis is conducted to quantify the environmental benefits of this circular strategy relative to conventional practices such as open-field residue burning and diesel-powered transportation. By combining engineering analysis with spatial and environmental modeling, this study provides a holistic and data-driven blueprint for advancing circular bioeconomy practices in tropical agriculture. The findings have implications not only for Costa Rica's pineapple industry but also for other biomass-intensive supply chains seeking to transition toward low-carbon, resource-efficient systems. In addition, the present study introduces a systems-level framework that explicitly integrates national-scale spatial biomass mapping, multi-objective optimization of decentralized infrastructure siting, process-level mass and energy balance evaluation, and environmental impact analysis within a single decision-support platform. The scientific novelty of this work lies in demonstrating how spatial logistics, energy recovery, and environmental performance can be jointly optimized to design a circular bioenergy system that is both technically feasible and scalable at national level.

2. Materials and methods

2.1. Pineapple utilization process

The pineapple utilization process modeled in this study is illustrated in Fig. 1, which outlines the integrated mass and energy flows of the proposed circular bioenergy system. The system begins with the collection and transportation of pineapple leaves and fruits from farms to decentralized processing depots (Unit operations 1a and 1b). At the depot, the leaves undergo mechanical juice extraction (Unit operation 2), separating the liquid fraction (juice) from the fibrous pulp. The juice, rich in soluble organics, is directed to an AD unit (Unit operation 3), where it is biologically converted into biogas and liquid digestate, the latter of which can be reused as a fertilizer. The resulting biogas is purified and compressed in an RNG production unit (Unit operation 4) to produce compressed RNG (CRNG) suitable for use as a clean transportation fuel. Simultaneously, the pulp fraction is sent to a drying and combustion system (Unit operation 5), where it is converted into heat and electricity. The CRNG is used for transportation and logistic activities including the harvesting and transport of pineapple fruits and leaves. The heat and electricity are used for on-site process energy demands, including mechanical juice extraction, anaerobic digestion, biogas upgrading, pulp drying, and refrigerated storage (Unit operation 6) of harvested pineapples at depot sites. System energy self-sufficiency is evaluated on an annual basis, with any remaining surplus available for external use. This closed-loop design exemplifies a circular bioeconomy approach by recovering energy from agricultural waste while reducing the carbon footprint of pineapple production and transport.

2.2. Pineapple production in Costa Rica

Costa Rica is a global leader in pineapple production, with approximately 65,000 ha of land dedicated to commercial pineapple cultivation [21]. Pineapple farming is concentrated in three major regions: the Huetar Norte, Atlantic Huetar, and Pacific regions (Fig. S1). These areas benefit from favorable climatic and soil conditions that enable continuous year-round production and support Costa Rica's prominent role in global pineapple exports [21]. A distinctive aspect of pineapple cultivation is the generation of substantial plant biomass beyond the

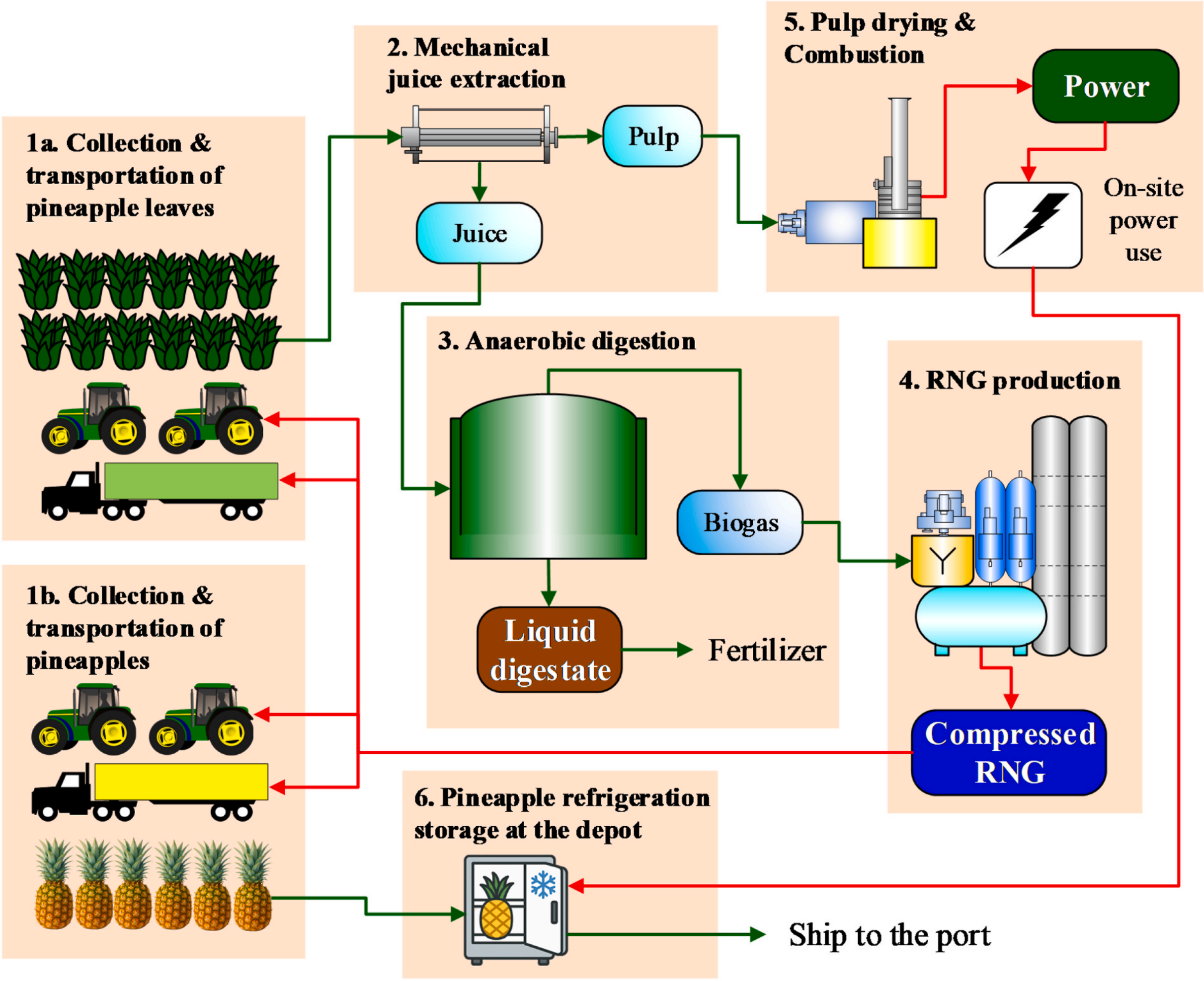


Fig. 1. Flowchart of the studied system *. The system includes six-unit operations of 1) collection of transportation of pineapple leaves and pineapples, 2) mechanical juice extraction, 3) anaerobic digestion of biogas production, 4) Compressed RNG production, 5) pulp drying and power generation, and 6) pineapple refrigeration storage at the depot.
*: The green lines are for mass flows, and the red lines are for energy flows. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

marketable fruit. On average, each hectare of pineapple farmland produces about 120 metric tons of pineapple leaves annually, while fruit yields approximately 60 metric tons per hectare per year, depending on local agronomic conditions [22]. This corresponds to an approximate mass ratio of leaves to fruit of 2:1, emphasizing the significant volume of lignocellulosic residue produced during harvest.

A schematic of the mass flow is presented in Fig. 2 based on the laboratory measurements and previous studies [13]. The system begins with the collection and transportation of 1 metric ton (MT) of wet pineapple leaves. During mechanical juice extraction, approximately 0.76 MT of juice and 0.18 MT of wet pulp are recovered, while 0.05 MT of leaves are lost in the process. The extracted juice undergoes anaerobic digestion, producing 13 m^3 of biogas with a methane concentration of 56% (v/v) and generating 0.74 MT of digestate, which can be repurposed as fertilizer. The biogas is then upgraded to CRNG, yielding 5.25 kg of CRNG. Simultaneously, the wet pulp is dried and combusted, converting 0.18 MT of wet pulp into 0.09 MT of dry pulp for energy recovery. As shown, the energy outputs from biogas and pulp combustion are intended to offset the energy requirements of feedstock collection, processing, and storage, which builds the foundation of a closed-loop, self-sustaining circular bioenergy system.

The characteristics of pineapple leaves, pineapple juice [12] and wet pulp [13] are summarized in Table 1. These compositional values provide essential inputs for evaluating the suitability of each material stream for energy recovery via AD and thermal conversion. Pineapple leaves exhibit a total solids (TS) content of 13.8%, with a high proportion of cellulose (22.6% of TS) and hemicellulose (26.1%), indicating their potential as a feedstock for biogas production. Nutrient contents such as nitrogen (1.1%), potassium (2.6%), and ash (6.1%) also influence the digestibility and downstream handling of the resulting digestate. In comparison, the juice has lower solids content (6.2%) but higher concentrations of crude protein (14%) and potassium (3.76%), while the wet pulp, with a TS content of 51.6%, is rich in cellulose (36.8%), hemicellulose (28.1%), and crude fat (4.0%), making it suitable for supplemental energy recovery through drying and combustion.

2.3. GIS-based analysis of locating depot sites

2.3.1. Mapping of pineapple and pineapple leaves distribution

Accurate spatial mapping is essential for identifying optimal depot locations for AD plants (fuel stations) and pineapple storage. To support this analysis, QGIS (Ver. 3.26) was employed to process and analyze geospatial data related to pineapple cultivation and transportation infrastructure in Costa Rica.

Prior to conducting spatial analyses and developing the GIS-based methodology, a comprehensive geodatabase was created by

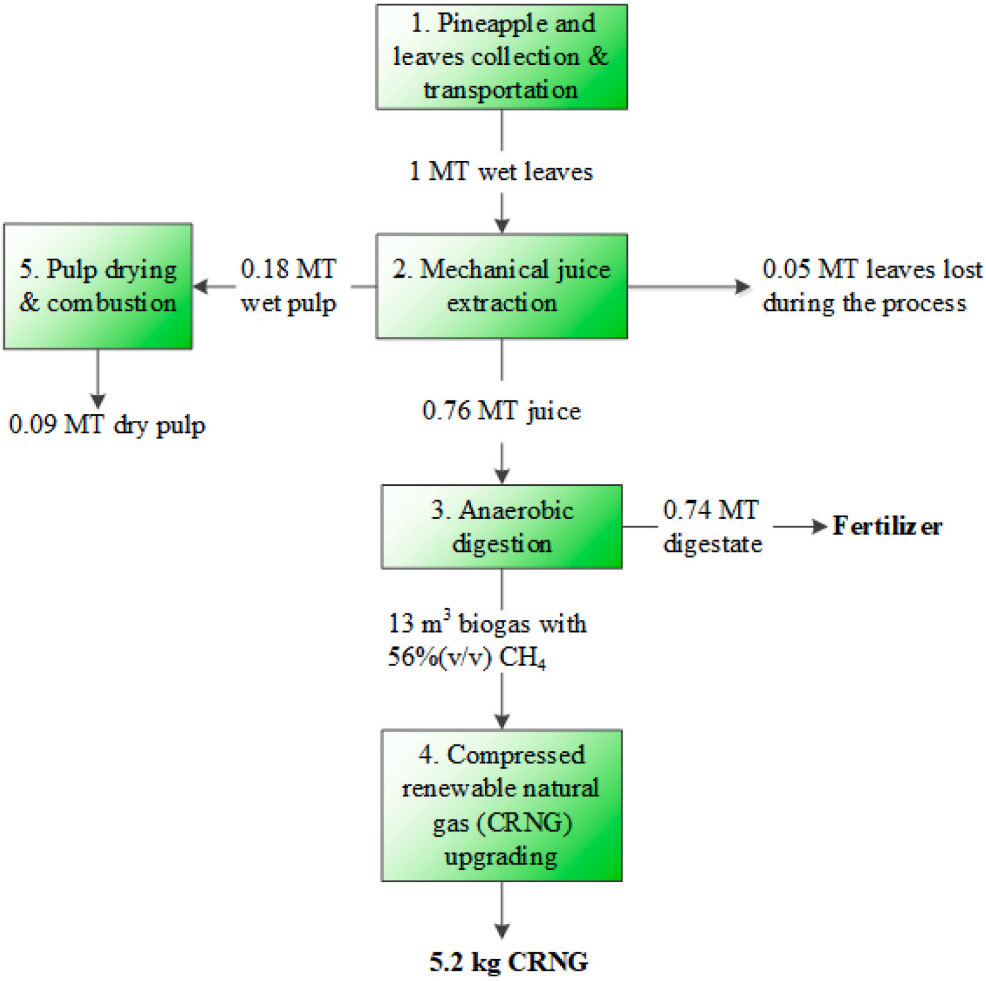


Fig. 2. Basic mass flow of the pineapple leaves utilization of CRNG production (based on 1 metric ton of wet pineapple leaves).

Table 1
Characteristics of pineapple leaves, juice, and wet pulp [12,13].

Parameter	Leaves	Juice	Wet pulp
Total solids (%)	13.8	6.2	51.6
Cellulose (% TS)	22.6	–	36.8
Hemicellulose (% TS)	26.1	–	28.1
Lignin (% TS)	7.3	–	5.1
Crude Protein (%TS)	6.9	14.0	5.7
Crude Fat (%TS)	3.0	3.5	4.0
Potassium (%TS)	2.60	3.76	0.56
Nitrogen (%TS)	1.10	2.24	0.91
Phosphorus (%TS)	0.11	0.18	0.08
Sulfur (%TS)	0.13	0.21	0.06
Ash (%TS)	6.10	10.02	1.65

integrating data from various sources, each providing specific spatial information required for the analysis. Administrative boundaries at national and sub-national levels were obtained from the United Nations Second Administrative Level Boundaries (SALB) database [23] and complemented with global administrative boundary layers from Opendatasoft [24]. National-scale agricultural statistics used to contextualize pineapple production were derived from the FAOSTAT database [25]. Base geospatial layers and boundary datasets ensuring spatial consistency among sources were obtained from the Humanitarian Data Exchange (HDX) platform [26]. The national road network and major highway infrastructure were visualized and verified using ArcGIS Online Map Viewer [27], while additional global cartographic reference layers were sourced from SimpleMaps for background mapping and spatial validation purposes [28]. Together, these datasets formed the geodatabase used to map pineapple production areas, transportation infrastructure, and logistical connectivity across Costa Rica.

The pineapple farm dataset contained 3,439 individual land parcels distributed across the country. Using QGIS, firstly a centroid calculation tool (the plugin “Centroid”) was applied to determine the geographic coordinates of each farm, while the field calculator tool was used to compute the area of each parcel in square kilometers. Once the farm areas were established, they were used to estimate the annual pineapple leaves production at the farm level. This was done by applying an average leaves yield factor (120 metric tons of leaves per hectare) to each farm area, generating a dataset containing the total annual pineapple leaves output per farm. The data were compiled into a master Excel table that was re-imported into QGIS to generate a pineapple leaves density map, which visualized the spatial distribution and concentration of leaves across the country. This map enabled the identification of regions with high leaves availability, guiding subsequent analysis of depot siting.

To facilitate spatially segmented optimization, the 3,439 farms were grouped into five geographic sections, based on regional clustering and density patterns. Within each section, farms producing more than 10,000 metric tons of pineapple leaves per year were identified as potential depot locations, serving as candidate sites for localized biogas production and fuel distribution. Using the selected candidate farms and applying the plugin “Shortest path (from point to layer)”, a shortest path network analysis was conducted in QGIS. This tool utilized the national road network to compute the shortest travel distances between each selected farm and the remaining farms within its section. A parallel analysis was performed to calculate the shortest road distance from each selected farm to the nearest major highway (primary road in Costa Rica, defined as "Ruta Nacional Primaria" in Spanish), representing a key criterion for logistical feasibility in fuel distribution. These two spatial metrics of 1) farm-to-depot distance and 2) depot-to-highway distance formed the basis for the MOO conducted in the following section. The spatial analysis outputs also informed the subsequent mass and energy balance calculations by providing realistic transport distance estimates tied to actual road infrastructure.

2.3.2. Multi-objective optimization (MOO) for depot siting

The depot concept in this study is designed to co-locate three key infrastructure components: an AD facility for biogas production, a CRNG fuel station, and a refrigerated storage unit for harvested pineapples. To ensure both operational efficiency and logistical feasibility, depot siting was guided by a MOO framework applied separately to each of the five regional sections defined in the spatial analysis. The optimization sought to balance two conflicting criteria: 1) minimizing the total transportation distance for moving pineapple leaves and fruit from all farms in the section to the selected depot, and 2) minimizing the distance from the depot to the nearest major highway, enabling efficient fuel distribution beyond the local region.

Candidate depot sites were first narrowed down based on a biomass availability threshold that only farms producing at least 10,000 metric tons of pineapple leaves per year were considered eligible. These high-yield farms were identified using QGIS software and served as initial candidate depot points for each section. For each candidate depot, the Shortest Path analysis results from Section 2.3.1 were compiled into Excel tables. These datasets were then used as inputs in R (version 4.5.1, an open-source programming language and software environmental for statistical computing) and R Studio (version 2025.05.1 Build 513, an integrated development environment (IDE) for R), to identify the depot farms that offered the best trade-offs between the two criteria. The MOO was implemented using the packages of mco, rgl, and dplyr in R.

Due to the inherently conflicting nature of the objectives that depots close to farms are often far from highways and vice versa, the optimization produced a set of non-dominated solutions for each section. These represent depot locations that cannot be improved in one objective without sacrificing the other. To reflect the relative importance of the two factors, a weight ratio of 60:40 was assigned to reflect the multi-functional role of the depots in the system. While farm proximity reduces local collection costs, highway connectivity governs the efficiency of downstream flows including CRNG distribution, refrigerated pineapple transport, and energy co-product delivery. Because these outbound logistics exert a stronger influence on overall system performance and emissions, highway access was weighted more heavily, while still preserving substantial consideration of farm proximity in the optimization. To select the final depot site for each section, a Pareto knee point analysis was applied. This method identifies the point on the Pareto frontier that offers the most balanced compromise between farm proximity and highway access.

The outcome of the MOO process was a single depot location selected for each of the five sections, forming the spatial backbone for the subsequent mass, energy, and life cycle analyses.

2.4. Technical analysis of RNG production from pineapple leaves

A detailed mass and energy balance was conducted for each regional section using the depot farm locations identified from the GIS MOO analysis. The mass and energy balance was developed using a calculation-based simulation framework implemented in Microsoft Excel [29]. The analysis integrates experimentally derived parameters from prior laboratory- and pilot-scale studies with literature-reported process yields, energy demands, and operational assumptions to quantify material and energy flows across each unit operation. The total amounts of pineapples and pineapple leaves, along with the corresponding transportation distances within each section, were derived from the spatial analysis. Key process parameters and assumptions used in the mass and energy balance are summarized in Table 2.

2.5. Environmental impact analysis

An environmental impact analysis was conducted to evaluate the environmental impacts of the proposed circular bioenergy system using pineapple leaves for CRNG production, relative to the conventional practice of open-field burning. The functional unit of the analysis is defined as the annual processing of pineapple leaves generated within each regional section, consistent with the biomass flows quantified in the mass and energy balance. All reported environmental impacts and avoided emissions are expressed relative to this functional unit to facilitate comparison with other relevant bioenergy and agricultural residue management studies. The analysis focuses on quantifying GHG emissions and air pollutants, using a life cycle inventory based on process parameters and emission factors summarized in Table 3.

The control scenario of on-site burning assumes that 80% of the TS in pineapple leaves are burned on-site following harvest. Emissions associated with this practice include methane (CH_4) and nitrous oxide (N_2O), both potent GHGs, as well as air pollutants such as particulate matter (PM), sulfur dioxide (SO_2), and nitrogen oxides (NO_X). Emission factors for these pollutants were obtained from literature and established environmental assessment sources and were applied to the total quantity of dry pineapple leaf mass burned annually within each regional section, as specified by the functional unit and detailed in Table 3.

In contrast, the CRNG production scenario incorporates avoided emissions from two primary sources: 1) Displacement of grid electricity through renewable power generated by the system, reducing CO_2 emissions by 0.00833 kg CO_2 per MJ of energy consumed, and 2) Replacement of diesel fuel with CRNG, reducing CO_2 emissions by 0.074 kg CO_2 per MJ of fuel consumed. The energy content of RNG was assumed to be 50 MJ/kg, based on its lower heating value (LHV). This value was applied consistently to convert CRNG production into energy-equivalent emission reductions related to the defined functional unit.

The system boundary for the environmental impact analysis includes the processes from pineapple residue collection through CRNG combustion in vehicles and excludes upstream impacts from pineapple cultivation. All emissions and avoided emissions were calculated on an annual, functional-unit basis aligned with the spatially resolved biomass availability in each section. The results of the environmental impact analysis were used to quantify potential reductions in GWP, air acidification, smog formation, and particulate emissions.

3. Results and discussion

3.1. Spatial distribution of pineapple and pineapple leaves

A detailed geospatial analysis was conducted to map the distribution of pineapple cultivation and associated leaves across Costa Rica (Fig. 3 and Fig. S2). The GIS-based dataset included 3,439 individual pineapple farm parcels, extracted from national agricultural land use records and processed using QGIS software. Each parcel was assigned a centroid coordinate and calculated area, enabling spatial attribution of biomass production based on average yield values (Fig. 3a).

Using the average production rates of 62.5 metric tons of pineapples and 125 metric tons of leaves per hectare per year, the total amounts of pineapples and pineapple leaves were estimated for each farm. The resulting pineapple leaf production values were merged into QGIS and visualized as a pineapple leaf density map, which revealed key geographic patterns in biomass availability. High-density clusters were observed primarily in the Huetar Norte and Atlantic Huetar regions, aligning with Costa Rica's primary pineapple production zones (Fig. S3). These regions contain the largest contiguous farm areas and the highest

Table 2
Parameters for the mass and energy balance analysis.

Unit operation	Parameter	Value or equation	Data source
1. Collection & transportation	Fuel consumption for pineapple leaves harvesting	2.4 kg CH_4/metric ton leaves harvested	[30]
	Fuel consumption for a class 8 semi-truck with 20 metric ton loading	0.2448 kg CH_4/km	Commercial data
	Size of the CRNG tank per truck	150 kg/truck	Commercial data
	Pineapples or pineapple leaves load per truck	20 metric ton/truck load	Commercial data
2. Mechanical juice extraction	Electricity consumption for mechanical crusher	65 MJ/metric ton leaves	Operational data
3. AD	Thermal energy demand	46 MJ/metric ton juice[a]	Calculated data
	Electricity energy demand	4.6 MJ/metric ton juice[b]	Operational data
	Hydraulic retention time	20 days	Experimental data[e]
	AD temperature	35 °C	Experimental data
	Biogas production	942 m^3/metric ton	Experimental data
	CH_4 content in the biogas	56% (v/v)	Experimental data
	CO_2 content in the biogas	44% (v/v)	Experimental data
	Methane heating value	50 MJ/kg	Data
4. CRNG upgrading	Raw biogas compression	0.22 kWh/m^3 raw biogas	Commercial data
	Biogas blowers	0.03 kWh/m^3 raw biogas	Commercial data
	Cooling	0.02 kWh/m^3 raw biogas	Commercial data
	CRNG compression	0.35 kWh/m^3 raw biogas	Commercial data
	Control and drying	0.01 kWh/m^3 raw biogas	Commercial data
	CH_4 purity in CRNG	96% (v/v)	Commercial data
	CH_4 recovery in CRNG	98% (v/v)	Commercial data
	CO_2 in the CRNG	1% (v/v)	Commercial data
5. Pulp drying	Thermal energy demand[c]	$Q = m \times C_p \times (100 - T_{Fiber}) + m \times \Delta h_v$	Calculated data
	Electricity for drying	2% of the thermal energy demand	Commercial data
6. Refrigeration storage[d]	Pre-cooling	30 kWh/metric ton pineapple	Commercial data
	Cooling storage	10 kWh/metric ton pineapples	Commercial data

[a] It is calculated using the heat equation: $Q = m \times C_p \times (T_{Digester} - T_{Environment}) \times (1 + 10\%)$, where Q is the heat demand (MJ), m is the mass of the juice (kg), C_p is the heat capacity of the juice (4.2 kJ/kg/C), $T_{Digester}$ is the digester temperature of 35C, $T_{Environment}$ is the average environment temperature of 25C in Costa Rica, 10% is the parasitic energy to maintain the reactor temperature.

[b] The electricity consumption of a digester operation is 10% of the heating energy.

[c] Q is the heat demand (MJ), m is the mass of the water in the wet fiber (kg), C_p is the heat capacity of the water (4.2 kJ/kg/C), 100 is the boiling temperature of 100C, T_{Fiber} is the average wet pulp temperature of 25C, Δh_v is the latent heat of water at 100C (2,244 kJ/kg).

[d] The forced air cooling (30 kWh/metric ton of electricity) is required to cool pineapples from ambient temperature to 7-10 C before the storage. During the storage, 10 kWh/metric ton pineapples is required to maintain the storage temperature of 7-10 C.

[e] The data were obtained from the bench-scale (10 L) continuous mixed stirred tank (CSTR) reactors that were run at University of Costa Rica.

Table 3
Life cycle inventory of pineapple leaves on-site burning and CRNG production[a].

Process	Item	Value	Unit	Reference
On-site burning (Control)	Amount of pineapple leaves burned	80	% of TS	[31]
	CH_4 emission factor	1.60	kg CH_4/metric ton dry pineapple leaves burned	[32]
	N_2O emission factor	0.21	kg N_2O/metric ton dry pineapple leaves burned	[32]
	Particulate matter (PM) factor	11.50	kg/metric ton dry pineapple leaves burned	[5]
	SO_2 emission factor	0.21	kg SO_2/metric ton dry pineapple leaves burned	[5]
	NOx emission factor	2.60	kg NOx/metric ton dry pineapple leaves burned	[33]
Pineapple leaves CRNG production	Reduction of CO_2 emission from generating renewable power	0.00833	kg CO_2/MJ energy consumed	[34]
	Energy content of RNG[b]	50	MJ/kg	
	Reduction of CO_2 emission from replacing diesel fuel	0.074	kg CO_2/MJ fuel consumed	[33]

[a] Emission factors are derived from peer-reviewed literature and established environmental assessment databases and represent emissions per unit of dry biomass burned or per unit of energy displaced, as indicated.

[b] The low heating value of RNG is used to run the analysis.

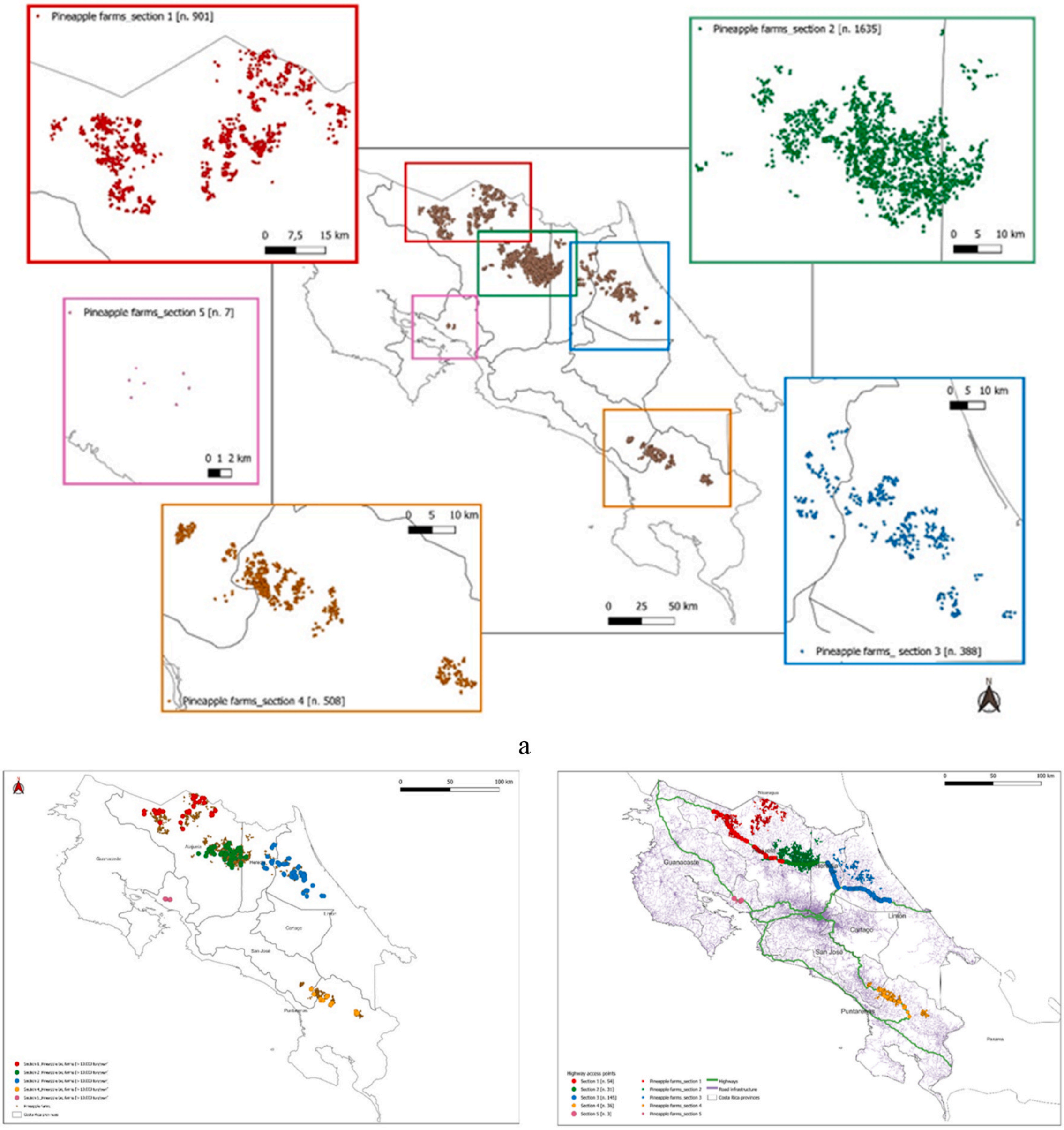
per-hectare productivity, making them strategic targets for biomass-based renewable energy development.

Of the 3,439 farms surveyed, only those producing more than 10,000 metric tons of pineapple leaves annually were identified as potential depot locations. These high-output farms were considered potential candidate sites for localized biogas production and fuel distribution (Fig. S4). Moreover, to support region-specific optimization and depot siting, the 3,439 farms were grouped into five geographic sections based on spatial clustering and logistical boundaries (Fig. 3a).

Within each section, pineapple fruit and leaf production volumes were aggregated to support localized mass and energy balance modeling for evaluating biogas production potential, fuel station placement, and pineapple storage. Farms producing over 10,000 metric tons of pineapple leaves per year were highlighted (Fig. 3b). This spatial segmentation forms the foundation for subsequent multi-objective optimization and scenario analysis, which provided critical transportation metrics. Using the “Shortest Path” tool in QGIS, farm-to-depot (Fig. S5) and depot-to-highway (Fig. S6) road distances were calculated for each farm, enabling precise modeling of energy use and emissions associated with biomass transport. Depot-to-highway distances were determined by analyzing the road network and considering all highway access points within each geographical section, as shown in Fig. 3d.

3.2. Multiple objective optimization to locate the depots

Following the spatial segmentation into five geographic sections, a



a

b

c

Fig. 3. Map of pineapple farms in Costa Rica. a. Distribution of pineapple farms, b. Potential depot locations within each geographic section, c. Highway access points to compute depot-to-highway road distances.

MOO was conducted to identify depot locations that minimize logistical burdens while maximizing access to transport infrastructure. Each depot is conceptualized as a co-located facility that integrates AD unit, CRNG compression and fueling station, and refrigerated pineapple storage. The optimization simultaneously considered two conflicting criteria of 1) minimizing total transport distance from farms to the depot for both pineapple fruits and leaves and 2) minimizing the distance from the depot to the nearest major highway.

To focus the optimization on high-yielding sites, only farms producing more than 10,000 metric tons of pineapple leaves per year were selected as candidate depot locations. Using QGIS software and R studio software, pairwise distance matrices were computed for each section: one capturing the farm-to-candidate depot distances, and the other representing candidate depot-to-highway connections based on the national road network (Fig. S6). Pareto-optimal depot configurations were generated using the MOO algorithm employed the Non-Dominated Sorting Genetic Algorithm II (NSGA-II). For each section, the algorithm yielded a set of depot locations that represent trade-offs between the two objectives. The resulting Pareto fronts are shown in Fig. 4, where each point represents a feasible depot location evaluated in terms of transport distance and highway accessibility. Rather than selecting an extreme solution that optimizes only one objective, a Pareto knee point analysis was applied to identify the depot location in each section that offers the most balanced compromise between farm proximity and highway access. The knee point corresponds to a solution beyond which further improvement in one objective would result in a disproportionately large penalty in the other. The depot locations identified through this knee-point criterion were selected as the final representative solutions and are summarized in Table 4 and Fig. 5 with their spatial coordinates and respective distances. These selected points therefore represent compromise solutions that minimize overall logistical burden while maintaining adequate access to major transportation corridors. The optimized depot locations provide a consistent and rational basis for the subsequent mass and energy balance modeling and environmental

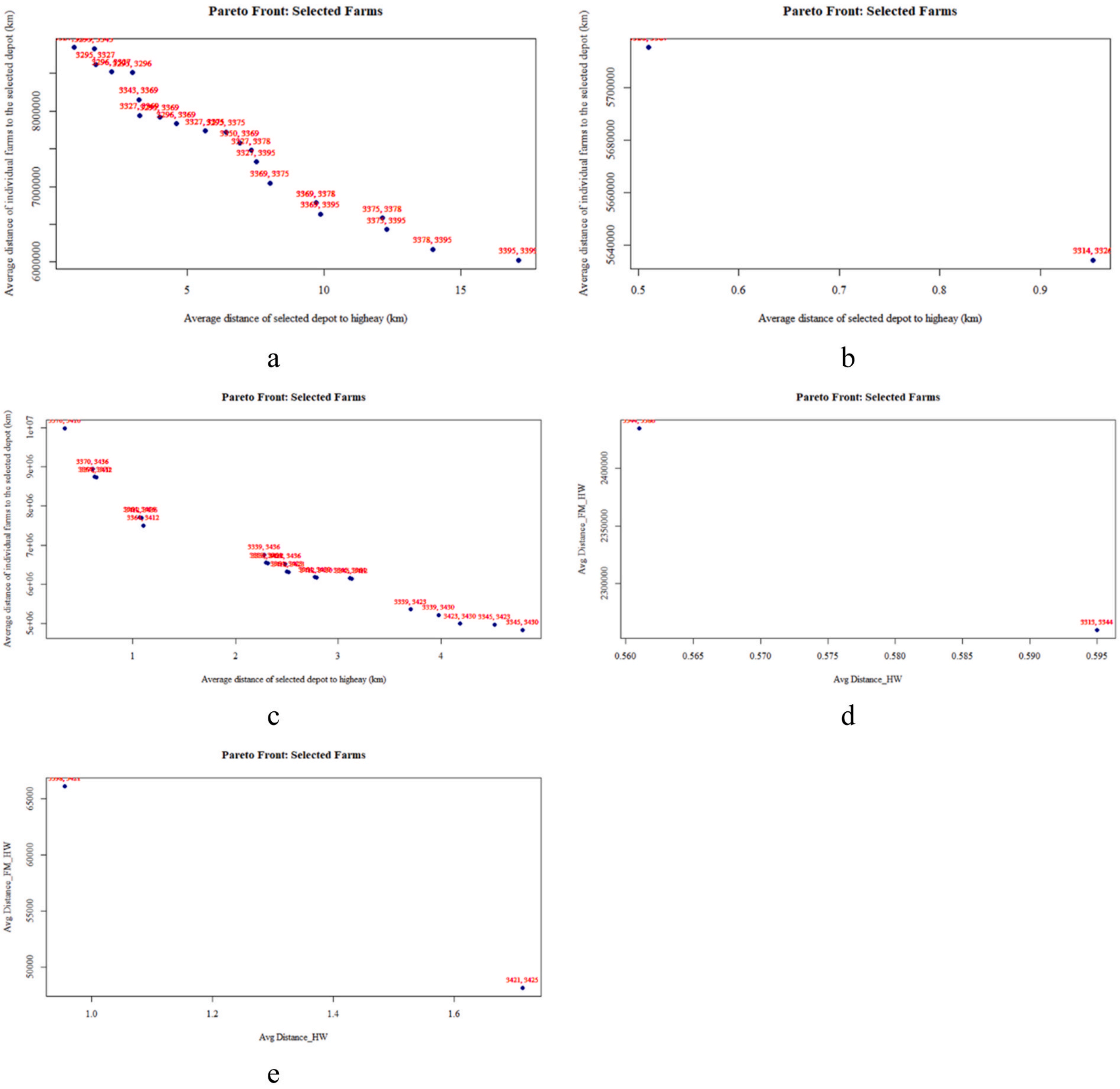


Fig. 4. NSGA-II solutions of depot locations for each section. a). Section 1; b). Section 2; c). Section 3; d) Section 4; e) Section 5.

impact evaluation.

Table 4
Selected depot locations for each section[a].

Section	Farm ID as the depot	Location (coordinates)[b]	Road distance to highway (km)	Road distance from all farms in the section to the depot (km)
1	3395	(-84.67, 10.88)	41.6	12472.725
2	3326	(-84.26, 10.43)	1.6	27965.213
3	3430	(-83.70, 10.29)	13.1	9625.634
4	3344	(-83.41, 9.16)	1.2	11883.507
5	3421	(-84.82, 10.08)	1.9	41.216

[a] A Pareto knee point analysis of the NSGA-II solutions was applied to obtain the selected depot locations.
[b] WGS 84 coordinate system.

3.3. *Technical analysis of pineapple leaves CRNG production*

The technical performance of the integrated pineapple leaves utilization and CRNG production system was evaluated through a comprehensive mass and energy balance across five geographically distinct sections (Sections 1-5). These calculations accounted for both the energy recovery from pineapple leaves and the handling and storage of harvested pineapple fruit. The results are summarized in Table 5, with detailed technical models provided in the supplemental data sheets.

In total, the system processes 7.524 million metric tons of pineapple leaves each year. Through mechanical extraction, this biomass yields 5.72 million metric tons of juice for AD and 688,504 metric tons of dry pulp for thermal energy recovery. In parallel, the system manages 3.76 million metric tons of pineapple fruit, which is refrigerated and stored at depot sites prior to export. AD of the extracted juice produces 39,530 metric tons of CRNG, while the residual 5.59 million metric tons of digestate can be used as a nutrient-rich soil amendment.

Energy consumption was distributed across multiple unit operations and transportation activities. Approximately 1.25 billion MJ/year of CRNG was used to support biomass logistics including the harvesting of leaves and the transportation of both leaves and fruit from farms to depot sites. Mechanical juice extraction required 489 million MJ/year, primarily for electrically powered crushing operations. AD operations

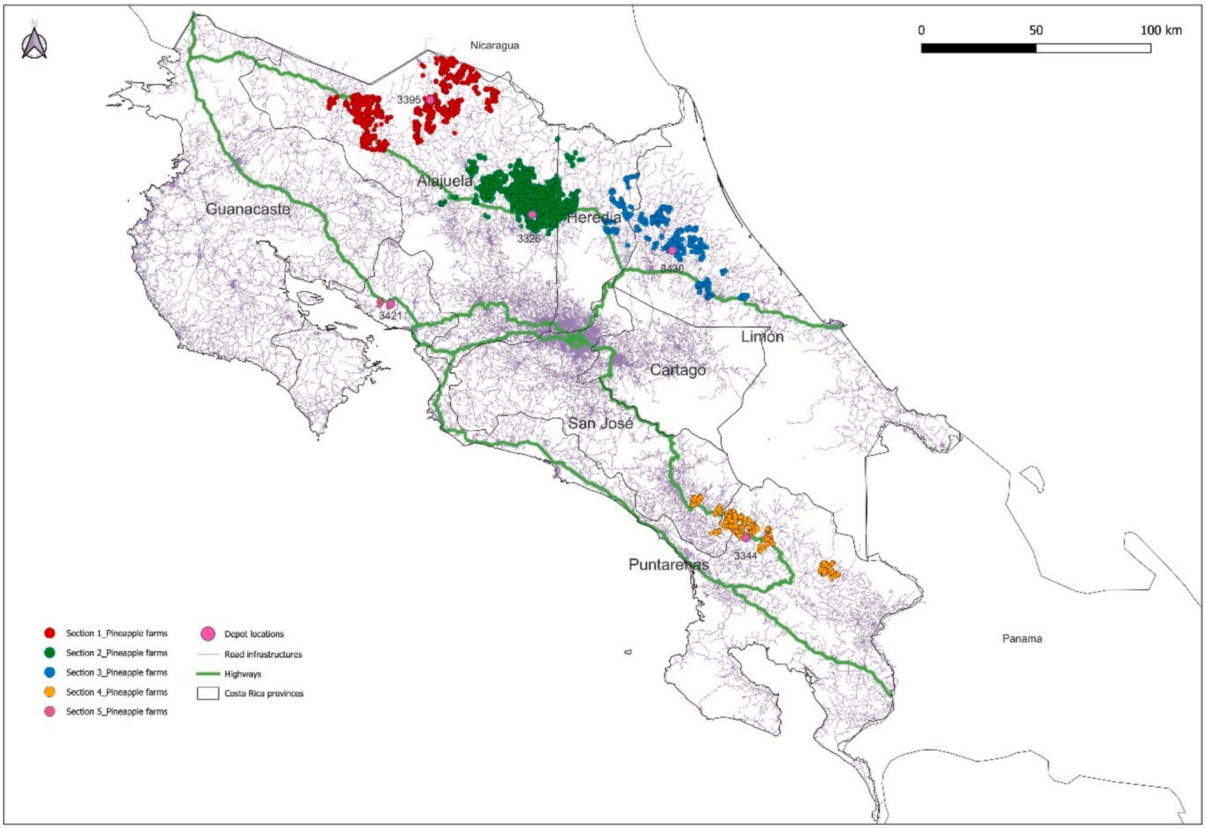


Fig. 5. Selected depot locations for each section.

Table 5
Mass and energy balance of individual sections and overall production [a].

	Section 1	Section 2	Section 3	Section 4	Section 5	Total
Depot location (Farm ID)	3395	3326	3430	3344	3421	
Mass balance (MT/year)						
Pineapple amount	616,469	1,595,994	990,969	504,500	54,381	3,762,313
Pineapple leaves amount	1,232,938	3,191,988	1,981,938	1,009,000	108,763	7,524,627
Juice	937,033	2,425,911	1,506,273	766,840	82,660	5,718,717
Dry pulp	112,814	292,067	181,347	92,324	9,952	688,504
CRNG	6,477	16,769	10,412	5,301	571	39,530
Digestate	916,365	2,372,404	1,473,050	749,926	80,837	5,592,582
Energy balance [b] (MJ/year)						
CRNG for leaves harvesting	-147,952,560	-383,038,560	-237,832,560	-121,080,000	-13,051,560	-902,955,240
CRNG for leaves transportation	-74,423,590	-68,439,324	-59,985,302	-28,206,566	-684,094	-231,738,876
CRNG for pineapple transportation	-37,211,301	-34,219,662	-29,992,651	-14,103,283	-342,047	-115,868,944
Electricity for mechanical juice extraction	-80,140,970	-207,479,220	-128,825,970	-65,585,000	-7,069,595	-489,100,755
Thermal energy for AD	-43,290,919	-112,077,083	-69,589,807	-35,428,008	-3,818,886	-264,204,703
Electricity for AD	-4,329,092	-11,207,708	-6,958,981	-3,542,801	-381,889	-26,420,471
Electricity for CRNG production	-27,075,735	-95,986,416	-59,598,948	-30,341,685	-3,270,617	-216,273,401
Thermal energy for pulp drying	-301,043,697	-779,380,528	-483,925,342	-246,365,260	-26,556,417	-1,837,271,244
Electricity for pulp drying	-6,020,874	-15,587,611	-9,678,507	-4,927,305	-531,128	-36,745,425
Electricity for pineapple refrigeration storage	-88,771,536	-229,823,136	-142,699,536	-72,648,000	-7,830,864	-541,773,072
Pulp energy	2,188,588,244	5,666,097,899	3,518,138,144	1,791,075,900	193,065,201	13,356,965,388
CRNG energy	323,865,220	838,463,811	520,610,757	265,041,719	28,569,606	1,976,551,113
Net energy output	1,692,194,189	4,567,322,463	2,809,661,297	1,433,889,711	158,097,710	10,661,165,370

[a] The detailed mass and energy balance are presented in the supplemental materials.

[b] The negative numbers are for energy inputs, and the positive numbers are for energy outputs.

consumed an additional ~290 million MJ/year, divided between thermal energy required to maintain digester temperature at 35 °C and electricity for internal mixing and pumping. Upgrading of raw biogas to vehicle-grade CRNG required 216 million MJ/year, which covered compression, membrane separation, cooling, and system control. The most energy-intensive process was pulp drying, which consumed 1.84 billion MJ/year to reduce moisture content for effective combustion. Meanwhile, the refrigerated storage of pineapple fruit required approximately 542 million MJ/year, including pre-cooling at 30 kWh/metric ton and cold storage at 10 kWh/metric ton to maintain fruit quality at 7–10 °C. Despite the significant operational energy demands, the system delivered significant net energy recovery, which confirms its technical viability as a self-sustaining circular bioenergy platform. Combustion of the dried pulp generated 13.36 billion MJ/year, attributed to the high calorific value of lignocellulosic biomass. In addition, CRNG production contributed an additional 1.98 billion MJ/year, which was sufficient to support all fruit and leaf harvesting and transport requirements. Together, these outputs yield a total net energy surplus of 10.66 billion MJ/year, indicating that the pineapple industry in Costa Rica has the capacity not only to meet its own energy needs but also to provide excess renewable energy to other agricultural and industrial sectors.

As for section-level performance, it varied based on the spatial distribution of pineapple farms, biomass availability, and logistical efficiency. Section 2 with the highest pineapple farms achieved the highest energy output at 4.57 billion MJ/year, benefiting from its large production volumes and favorable depot-to-highway proximity. Sections 1 and 3 also performed well, producing 1.69 billion and 2.81 billion MJ/year, respectively. Even Section 5, which represented a relatively small production area, maintained a positive net energy balance of 158 million MJ/year. The results from individual sections demonstrate the scalability and resilience of the integrated pineapple leaves utilization and CRNG production system in Costa Rica.

Beyond energy recovery, the integration of pineapple fruit logistics into the depot system significantly enhances the circularity of the overall supply chain, creating new agro-industrial opportunities. Co-locating AD units, CRNG fueling infrastructure, and refrigerated storage allows the energy recovered from pineapple leaves to directly support cold-chain operations, reducing dependence on fossil fuels and reinforcing local energy autonomy. This integrated, resource-efficient approach elevates pineapple leaves from an environmental liability to a valuable co-product, supporting both environmental and economic resilience. Collectively, the results demonstrate strong technical performance and high adaptability of the CRNG systems across diverse logistical and production scenarios.

3.4. Environmental impact analysis of the pineapple leaves CRNG production

A comparative environmental impact analysis was conducted to quantify the environmental benefits of the pineapple leaves CRNG system relative to conventional open-field burning practices. The analysis focused on four impact categories: GWP, particulate matter emission potential, air acidification potential, and smog formation potential. The results are illustrated in Fig. 6, and represent the aggregated performance of the national system integrating all five geographic sections. Environmental impact results for individual sections are presented in Fig. S8–S12 in the supplementary materials.

In terms of GWP, the CRNG system achieved a net reduction of approximately 443,726 metric tons of CO_2-equivalent per year. This includes a reduction of −53,723 metric tons of CO_2-e attributed to the displacement of gasoline by CRNG, and another reduction of −27,487 metric tons of CO_2-e from replacing grid electricity with power generated from pulp combustion. In contrast, the baseline scenario of on-site burning released 43,613 metric tons of CO_2-e from CH_4 and 67,600 metric tons of CO_2-e from N_2O, totaling 111,213 metric tons of CO_2-e/year in emissions. These results demonstrate the substantial climate mitigation potential achieved by diverting pineapple leaves from open burning to renewable energy production.

For particulate matter emissions, the open burning scenario released 14,927 metric tons per year of fine particulates. This category is of particular concern for public health, as particulate matter emissions contribute to respiratory illness and degrade regional air quality. In contrast, the CRNG system eliminated particulate matter emissions entirely, as both AD and combustion of dried pulp occur in controlled environments with emission capture or reuse.

The results for air acidification potential also favor the CRNG system. Open-field burning generated a combined 2,316 metric tons of SO_2-equivalent emissions annually, including 273 t from sulfur dioxide (SO_2), 153 t from N_2O, and 1,890 t from nitrogen oxides (NO_X). These

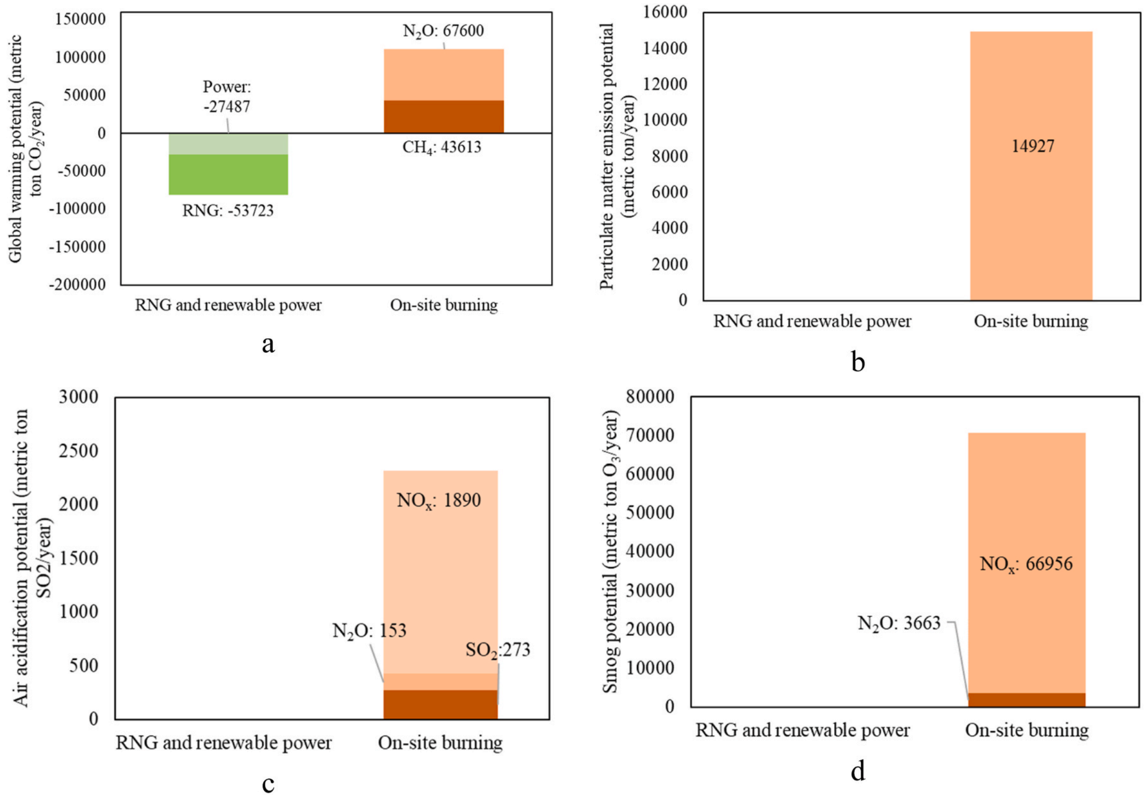


Fig. 6. Environmental impact analysis of overall pineapple leaves utilization for the entire Costa Rica. a). GWP; b). Particulate matter; c). Air acidification; d) Smog.

compounds contribute to acid rain and soil degradation. The CRNG pathway eliminated air acidification potential emissions through controlled combustion and the absence of open biomass burning.

With respect to smog formation potential, the open burning practice was responsible for 70,619 metric tons of O_3-equivalent emissions per year, primarily from 66,956 metric tons of NO_X and 3,663 metric tons of N_2O. In contrast, the CRNG pathway produced negligible quantities of ozone precursors, representing a near-total elimination of smog-forming emissions from the system.

Overall, the environmental impact analysis indicates that the CRNG strategy provides substantial benefits across all assessed categories. The avoidance of GHGs, particulate matter, acidifying gases, and ozone precursors illustrates the strength of the circular bioenergy model not only in carbon mitigation but also in improving air quality, protecting ecosystem health, and promoting ecotourism. These benefits are particularly relevant in rural agricultural regions where open burning is still a widespread practice.

When expressed relative to the defined functional unit, the environmental performance of the studied pineapple-leaf-to-CRNG system is comparable to, and in several impact categories exceeds, values reported in the literature for agricultural residue–based bioenergy pathways. Previous studies on crop residue management have reported GHG emission reductions associated with avoiding open-field burning in the range of approximately 0.5–1.5 t CO_2-e per metric ton of dry biomass processed, depending on residue type and combustion assumptions [35]. Similarly, renewable natural gas production from agricultural residues and organic wastes has been shown to reduce lifecycle GHG emissions by 60–90% relative to diesel or fossil natural gas when used as a transportation fuel [36], corresponding to avoided emissions on the order of 0.06–0.09 kg CO_2 per MJ of fuel displaced [37]. Reported particulate matter emissions from open biomass burning commonly range from 10 to 30 kg PM per metric ton of dry residue [38] whereas controlled anaerobic digestion and downstream energy utilization substantially reduce or eliminate direct particulate emissions. When normalized to the annual pineapple leaf biomass processed in this study, the combined effects of avoided open-field burning and fossil fuel displacement place the proposed system at the upper end of reported environmental benefits, particularly with respect to particulate matter, smog-forming emissions, and air acidification potential. These comparisons highlight the advantage of integrating spatial optimization, process-level energy recovery, and controlled emission management within a circular bioenergy framework.

4. Conclusions

This study demonstrates a scalable circular bioenergy strategy for Costa Rica's pineapple industry by converting pineapple leaves into CRNG and renewable power through an integrated, systems-level approach. By coupling spatial analysis, optimization, and process-level energy evaluation, the proposed framework shows how agricultural residues can be transformed from a disposal challenge into a valuable energy resource. At the national scale, processing approximately 7.52 million metric tons of pineapple leaves annually enables the system to meet internal energy demands while generating a net energy surplus of 10.66 billion MJ per year, highlighting the feasibility of enhancing energy self-sufficiency within agricultural supply chains. The environmental impact analysis further indicates order-of-magnitude reductions in GHG emissions ($\approx 10^5$ metric tons CO_2-e per year) compared to open-field burning, along with substantial improvements in air quality. Overall, this work demonstrates the value of integrating geographic information systems, MOO, calculation-based mass and energy balances, and emission-factor-based environmental evaluation within a unified framework. While focused on Costa Rica's pineapple industry, the approach is broadly applicable to other biomass-intensive agricultural systems seeking circular, low-carbon, and resource-efficient development pathways.

CRediT authorship contribution statement

Adelina Yuning Liao: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Emanuele Spizzirri:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **María José Rodriguez-Vasquez:** Visualization, Validation, Resources, Investigation. **Mauricio Bustamante-Roman:** Writing – review & editing, Validation, Resources. **Juan-Pablo Rojas-Sossa:** Writing – review & editing, Validation, Resources. **Attilio Toscano:** Writing – review & editing, Visualization, Validation. **Francesca Valenti:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2026.125709.

Data availability

The data supporting this article have been included as part of the Supplementary Information.

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