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COVER: Figure 1. Cloned cocoa in its natural state. Cocoa (*Theobroma cacao* L.) Husk Potential for Biogas and Biofertilizer Production by Ísis Costa dos Santos et al. J Bioeng. Tech. Health 2026;9(9):897.

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Carbon Footprint of *Agave sisalana* Leaf Processing

Lorena Rodrigues Cunha^{1*}, Ana Nadjia Lopes Lucas¹, Matheus Martins Teixeira Cota¹, Diego Lima Medeiros², Edna dos Santos Almeida¹

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The aim of this work is to carry out a Life Cycle Assessment (LCA) to quantify the carbon footprint of 1 ton of sisal fiber production, including the stages of decortication, sun drying, brushing, grading, and baling. Diesel consumption significantly contributes to the carbon footprint during the decortication stage of sisal leaf processing for fiber extraction. It was observed that diesel consumption is a main contributor to the carbon footprint in the sisal leaf processing in the decortication stage for fiber extraction. The mixtures of diesel and biodiesel in 86:14 and 80:20 (on a volumetric basis) can reduce 5% and 10% of the carbon footprint, respectively, highlighting the potential strategy to make sisal fiber production more sustainable.

Keywords: *Agave sisalana*. Vegetable Fiber. Environmental Impact. Greenhouse Gas (GHG). Life Cycle Assessment.

The *Agave sisalana* plant is cultivated in the semi-arid region in Northeast Brazil. This agricultural activity is classified as low-tech, typically with no irrigation and low productivity. During leaf processing, a substantial amount of organic waste is generated and, mostly, these residues are distributed on the field by hand to restore nutrients to the soil [1].

Sisal fibers are extracted from the leaves of *Agave sisalana*. This process constitutes an economic activity that is relevant for job and income generation in this region [2].

Sisal fiber is an intermediate product used to produce twine, rope, carpets, and bags, and has also been used in composites in the automotive and civil construction industries [1].

In this context, it's important to evaluate the environmental impact of *Agave sisalana* leaf processing. To this end, the Life Cycle Assessment (LCA) is a widely used standardized methodology to quantify the environmental impacts of a product system throughout its life cycle [1]. Material Flow Analysis (MFA) is used

to evaluate the mass balance, supporting the LCA.

Previous LCA studies have been conducted to assess the environmental impacts associated with sisal fiber production [1]. These studies reported that the energy consumption and waste generation associated with sisal leaf processing are main drivers of the environmental impact of sisal fiber production.

The sisal leaf processing involves the following stages: fiber extraction or decortication, drying, brushing, baling, and grading. The decortication occurs in the field with the use of diesel machinery in most sisal farms in Brazil [1].

In this context, the aim of this work is to carry out an LCA to assess the carbon footprint of 1 ton of sisal fiber production. Proposed scenarios for the replacement of diesel by biodiesel and these fuel mixtures were evaluated. In this regard, this study supports decision-making for improved environmental practices in the sisal supply chain.

Materials and Methods

Material Flow Analysis (MFA) and attributional Life Cycle Assessment (LCA) methods were used to assess the mass balance and global warming potential performance of the *Agave sisalana* leaf processing, respectively.

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The MFA was carried out using STAN® software version 2.7.10. The mass balance data were obtained from Broeren and colleagues [1] based on the yield rates of the sisal leaf processing stages, consumption of diesel and electricity, and moisture of the dried sisal fiber (13% w/w).

For the moisture content of the wet fiber, it was assumed to be 65% according to Widyasanti and colleagues [2]. The mass of evaporated water during drying was estimated using mass balance calculations.

The reference flow was 1 ton of sisal fiber produced. The sisal fiber production involves decortication, sun-drying, brushing, grading, and baling. The resulting outputs include processing residue, water vapor from drying, and baled sisal.

LCA methodology based on ABNT NBR ISO 14044 and 14067 [3,4] was used to evaluate the carbon footprint. The product system was extended from gate to gate to cover only the leaves processing (Figure 1).

Table 1 shows the input and output flows of sisal leaf processing to produce 1 ton of sisal fiber in the evaluated scenarios (SC1-SC4).

Figure 1. Product system of the sisal leaves processing.

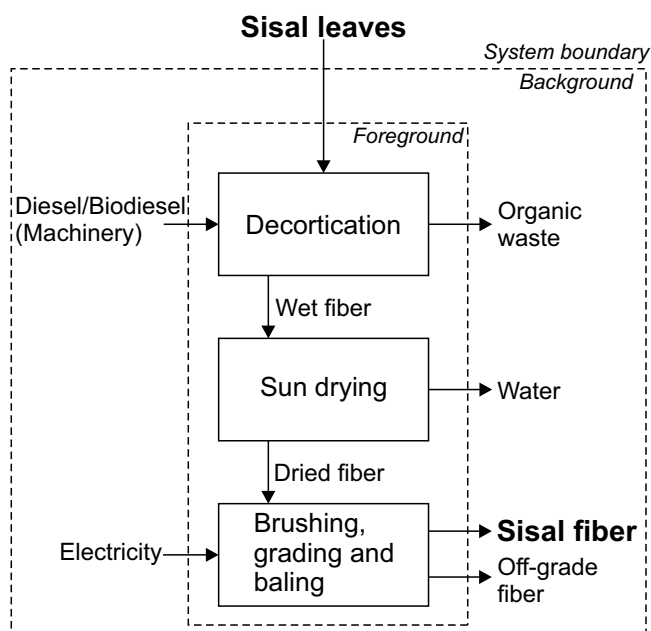


Table 1. Foreground inventory for 1 ton of sisal fiber production in the evaluated scenarios.

Parameter	Unit	SC1	SC2	SC3	SC4
Decortication					
Input					
Sisal leaves	kg	31000	31000	31000	31000
Diesel (machinery)	kg	34.5	-	-	-
Diesel/ Biodiesel (machinery)	kg	-	34.58	34.81	-
Biodiesel (machinery)	kg	-	-	-	38.22
Output					
Wet fiber	kg	2600	2600	2600	2600
Waste	kg	28400	28400	28400	28400
Sun drying					
Input					
Wet fiber	kg	2600	2600	2600	2600
Output					
Water	kg	1350	1350	1350	1350
Dried fiber	kg	1250	1250	1250	1250
Brushing, grading and baling					
Input					
Dried fiber	kg	1250	1250	1250	1250
Electricity	MJ	28	28	28	28
Output					
Fiber baled	kg	1000	1000	1000	1000
Waste (off-grade fiber)	kg	250	250	250	250

The evaluated scenarios differ regarding the fuel used in the machinery for decortication. The first scenario (SC1) considered the use of 100% diesel fuel, while the second scenario (SC2) considered a diesel mixture with 14% biodiesel, the third scenario (SC3) considered the mixture with 20% biodiesel, and the fourth scenario (SC4)

considered 100% biodiesel. The remaining mass and energy flows are described in Table 1.

The product system was modeled using OpenLCA® software version 2.5 with the Ecoinvent database version 3.10. The impact method was the Global Warming Potential (GWP) for 100 years, which quantifies the greenhouse gas (GHG) emissions in carbon dioxide equivalent (CO₂ eq).

Results and Discussion

MFA for sisal processing is shown in Figure 2. According to Broeren and colleagues [1], 31 tons of sisal leaves are used for 1 ton of sisal fiber production and 0.25 tons of waste generation (off-grade fiber). However, those authors did not report the quantities of residues during decortication.

Then, this value was calculated in this study considering the 65% moisture of the wet fiber [2], 13% moisture of the dried fiber and the production data provided by Broeren and colleagues [1] in the mass balance calculation. Then, it was estimated that the decortication process produces 2.6 tons of wet fiber and generates 28.4 tons of organic waste (Figure 2), the latter representing the major output quantity which is disposed of in the field as residue. The organic waste can be a resource

for further processing to add value to this material, for example, through the production of biochar, biogas, composite panels, or enzyme extraction [5,6]. But in the sisal region of Brazil, this is not a typical practice.

It is noteworthy that the sisal processing generates 0.25 tons of off-grade fiber, and the use of this residue as a feedstock for bioenergy or biomaterials represents an important way for environmental impact reduction.

Figure 3 presents the results of the carbon footprint for 1 ton of sisal fiber production in the evaluated scenarios.

Figure 3 shows the impact of different fuel blend scenarios on the carbon footprint for the production of 1 ton of sisal fiber. Scenarios SC1, SC2, and SC3 display very similar values, around 220 kg CO₂-eq, reflecting the dominant role of diesel consumption in the decortication process. Only in scenario SC4 is a more significant reduction observed, with emissions reaching approximately 190 kg CO₂-eq, which highlights the direct effect of full substitution of fossil diesel by biodiesel. This difference indicates that marginal changes in the fuel mix (as in SC2 and SC3) result in limited gains, whereas complete substitution (SC4) is the only approach capable of significantly altering the emission profile of the process.

Figure 2. Mass balance of the sisal fiber production system.

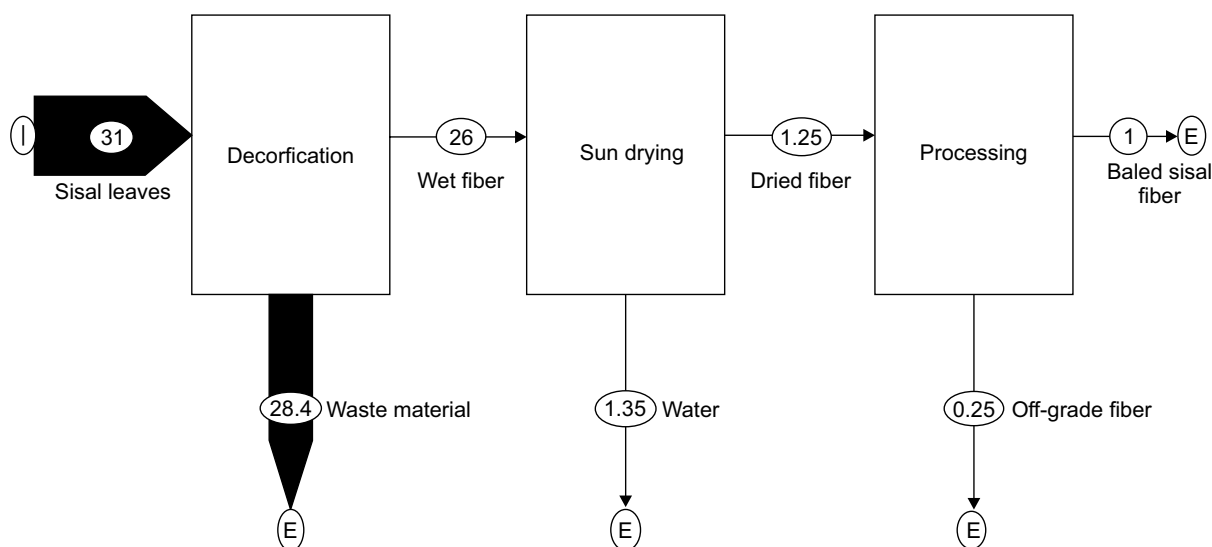


Figure 3. Carbon footprint for 1 ton of sisal fiber production in the evaluated scenarios.

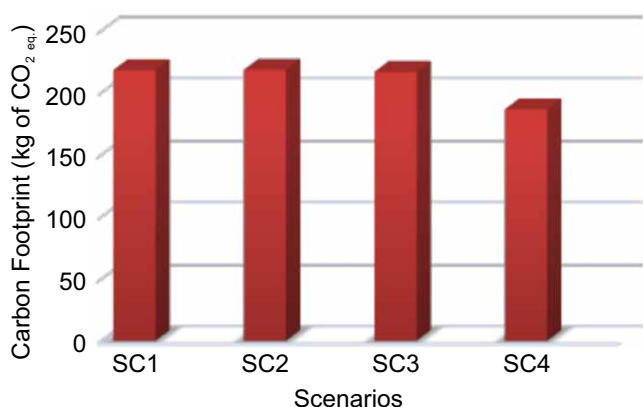
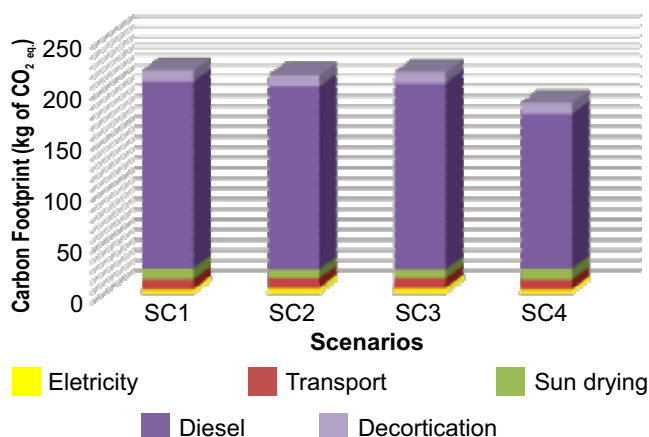


Figure 4 presents the relative contribution of each process stage in the different scenarios. The comparison among scenarios shows that changes in fuel composition affect the intensity of emissions but do not substantially alter the hierarchy between the process stages.

The total carbon footprint reaches 218.17 kg CO₂-eq per ton of processed sisal, with diesel accounting for 89% of total emissions, highlighting decortication as the main critical stage. Transport (10%) and electricity (1%) appear as secondary contributors with marginal impact. This configuration reinforces the strong dependence of the agro-industrial stage on fossil fuel, limiting the

Figure 4. Carbon footprint: the relative contribution of each process stage in the evaluated scenarios.



potential for carbon footprint reduction without substantial changes in the process energy matrix [2,4].

The comparison among scenarios SC2, SC3, and SC4 reveals a gradual reduction in the carbon footprint as the proportion of biodiesel in the blend used in decortication machinery increases. In SC2, with 14% biodiesel, total emissions show a modest reduction of approximately 5.25% compared to SC1, reaching 206.6 kg CO₂-eq. Diesel remains the main source of impact (86%), followed by transport (10%) and electricity (4%). Although partial diesel substitution by biodiesel brings benefits, the reduction is relatively modest, suggesting the need for higher substitution rates or more efficient technologies [7].

In SC3, with 20% biodiesel, emissions decrease to approximately 194.7 kg CO₂-eq, representing a 10.67% reduction compared to SC1. Diesel still accounts for 91% of the impact, while transport and electricity together contribute less than 10%. These results indicate that, despite the progressive decrease in emissions, increasing the biodiesel share leads to diminishing returns, pointing to the need for deeper decarbonization alternatives [8].

In SC4, where fossil diesel is fully replaced by biodiesel, emissions are reduced to around 190 kg CO₂-eq, representing the most significant reduction among the evaluated scenarios. Unlike previous cases, the impact of diesel disappears, and emissions are mainly associated with transport (10%) and electricity (1%). Despite this improvement, it is important to note that stages such as sun drying, transportation, and electricity supply maintain a lower share (<5%), suggesting that the decarbonization of sisal processing primarily depends on replacing diesel in the shredding process [9]. However, literature indicates that the carbon footprint of biodiesel varies significantly depending on the biomass source and agricultural management, highlighting the need to evaluate trade-offs such as land use change [10]. Thus, although the evaluated scenarios show a trajectory toward lower GHG emissions, full environmental viability requires

considering low-carbon biodiesel suppliers and more efficient machinery [11]. When comparing the four scenarios, it is evident that, although all show a trend toward reduced emissions relative to the baseline scenario, the differences mainly reflect variations in the biodiesel fraction used. Scenarios with higher biodiesel content exhibit the lowest carbon footprints, showing that increasing the renewable fuel fraction is an effective measure, yet not sufficient. Additional strategies, such as using renewable electricity, optimizing logistics and energy use, recovering residual heat, and integrating process by-products, could further reduce emissions and enhance environmental efficiency. Scenarios with lower biodiesel fractions show limited reductions, suggesting that partial measures may be insufficient to achieve full environmental sustainability. Therefore, a consistent transition toward more sustainable sisal processing requires an integrated approach, combining renewable fuels, operational efficiency, and resource utilization, while carefully considering environmental and economic trade-offs.

Additionally, it is highlighted that the appendix contains the simulation data sheet, where the carbon footprint results are presented in detail, with the contributions broken down by category for each evaluated scenario. This supplementary material enhances the understanding of impact sources, ensuring greater transparency of the results and enabling more in-depth comparative analyses.

The Sankey diagram illustrates the distribution of GHG contributions across the production stages, with diesel burning during decortication standing out as the dominant contributor to the carbon footprint of 1 ton of sisal fiber, while other processes have comparatively smaller impacts.

The Sankey diagram shows the different phases of the sisal production chain with their carbon footprint contributions, being important for identifying hotspots and opportunities for mitigation.

The arrows representing diesel consumption are noticeably thicker, showing their significant

contribution to the total carbon footprint.

On the other hand, smaller flows, such as electricity use, appear as thinner arrows, representing a smaller fraction of the impact compared to diesel use. This allows us to visualize how resources are distributed throughout the product system and where the greatest environmental impacts are concentrated, which can guide efforts to optimize these stages (Figure 5).

Additionally, sisal fiber acts as a biogenic carbon sink, retaining atmospheric CO₂ during plant growth and storing it within its structure over the product's lifetime. This storage capacity is particularly relevant in Life Cycle Assessment, since it can offset part of the emissions generated during cultivation, transport, and processing. As a result, even under relatively inefficient production conditions, sisal fiber may present a favorable net carbon balance, reinforcing its potential to be accounted for as a source of carbon credits in sustainability frameworks [10,11].

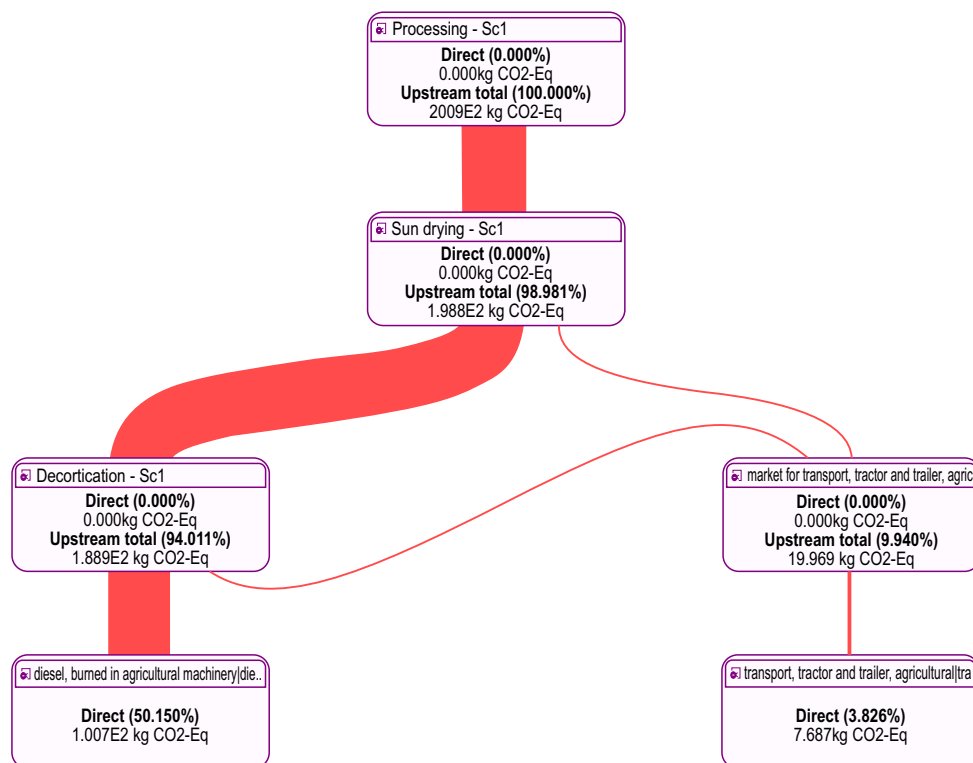
Conclusion

The assessment of carbon footprint of sisal processing to obtain 1 ton of sisal fiber was carried out and showed that the energy use, mainly due to diesel consumption, is the major contributor to this environmental impact.

The results indicate that sisal decortication is the most intensive stage, both in terms of energy demand and carbon footprint, when compared to the remaining processing stages (fiber brushing, grading and baling) which use electricity. Diesel and mixtures with biodiesel consumed for the decortication process represent the major contribution to the carbon footprint.

This research shows a 33.29% impact reduction due to diesel replacement by biodiesel.

However, this option needs to adapt the equipment called "Paraibana machinery" used in decortication, which is still not common practice. Therefore, when using the fuel mixtures of 86:14 and 80:20 (on a volumetric basis) for diesel and

Figure 5. Sankey diagram of the carbon footprint for the production of 1 ton sisal fiber.

biodiesel, the carbon footprint reduction is 5% and 10%, respectively.

It is noteworthy that with the Brazilian Federal Law No. 14.993/24, known as the Future Fuel Law, the addition of biodiesel to diesel is planned to reach 20% by 2030. This mandatory increase of biodiesel in the fuel mixture is a strategy to support the carbon footprint reduction in sisal fiber production.

Acknowledgement

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Appendix

Figure 1.S. Carbon footprint for 1 ton of sisal fiber production in SC1.

Impact category: Climate change | Global warming potential (GWP100)

Contribution	Process	Required amount	Total result [kg C...	Direct contributi...
✓ 100.00%	Processing - SC1	1.00000 kg	218.17570	
✓ 98.96%	Sun drying - SC1	1250.00000 kg	215.90876	
✓ 93.97%	Decortication - SC1	2600.00000 kg	205.02772	
✓ 88.99%	diesel, burned in agricultural machinery diesel, b...	1440.01679 MJ	194.14668	100.98875
> 16.18%	market for agricultural trailer agricultural trailer ...	5.21286 kg	35.30198	
> 12.50%	market group for diesel diesel Cutoff, U - GLO	32.00037 kg	27.27121	
> 08.49%	market for tractor, 4-wheel, agricultural tractor, 4...	2.23203 kg	18.52618	
> 05.53%	market for shed shed Cutoff, U - GLO	0.04982 m ²	12.05856	
✓ 04.99%	market for transport, tractor and trailer, agricultur...	28.00000 t*km	10.88104	
> 04.99%	transport, tractor and trailer, agricultural transpor...	28.00000 t*km	10.88104	3.85268
✓ 04.99%	market for transport, tractor and trailer, agricultur...	28.00000 t*km	10.88104	
> 04.99%	transport, tractor and trailer, agricultural transpor...	28.00000 t*km	10.88104	3.85268
✓ 01.04%	market for electricity, low voltage electricity, low ...	28.00000 MJ	2.26694	0.00196
> 01.00%	electricity voltage transformation from medium t...	28.30893 MJ	2.18040	

Figure 2.S. Carbon footprint for 1 ton of sisal fiber production in SC2.

Impact category: Climate change | Global warming potential (GWP100)

Contribution	Process	Required amount	Total result [kg C...	Direct contributi...
✓ 100.00%	Processing - SC2	1000.00000 kg	218.48987	
✓ 96.10%	Sun drying - SC2	1250.00000 kg	209.96719	
✓ 91.16%	Decortication - SC2	2600.00000 kg	199.17775	
✓ 86.19%	diesel-B14, burned in agricultural machinery dies...	1439.91120 MJ	188.31684	87.00789
✓ 16.04%	market for agricultural trailer agricultural trailer ...	5.21248 kg	35.04022	
> 16.00%	agricultural trailer production agricultural trailer ...	5.19840 kg	34.96632	3.11904E-5
> 00.03%	agricultural trailer production agricultural trailer ...	0.01407 kg	0.07390	8.44422E-8
> 10.48%	market group for diesel diesel Cutoff, U - GLO	27.51830 kg	22.88828	
> 08.39%	market for tractor, 4-wheel, agricultural tractor, 4...	2.23186 kg	18.32039	
> 06.19%	esterification of soybean oil fatty acid methyl est...	4.47972 kg	13.51797	
> 05.28%	market for shed shed Cutoff, U - GLO	0.04982 m ²	11.54209	
> 04.97%	market for transport, tractor and trailer, agricultur...	28.00000 t*km	10.86091	
> 04.94%	market for transport, tractor and trailer, agricultur...	28.00000 t*km	10.78944	
> 03.90%	market for electricity, low voltage electricity, low ...	28.00000 MJ	8.52268	0.00203

Figure 3.S. Carbon footprint for 1 ton of sisal fiber production in SC3.

● Impact category Climate change | Global warming potential (GWP100)

Contribution	Process	Required amount	Total result [kg C...	Direct contributi...
▼ 100.00%	Processing - SC3	1000.00000 kg	216.72355	
▼ 96.07%	Sun drying - SC3	1250.00000 kg	208.20086	
▼ 91.09%	Decortication - SC3	2600.00000 kg	197.41129	
▼ 86.08%	diesel-B20, burned in agricultural machinery dies...	1440.08970 MJ	186.55026	81.02931
> 16.17%	market for agricultural trailer agricultural trailer ...	5.21312 kg	35.04529	
> 09.83%	market group for diesel diesel Cutoff, U - GLO	25.60159 kg	21.29405	
> 08.91%	esterification of soybean oil fatty acid methyl est...	6.40040 kg	19.31485	
> 08.45%	market for tractor, 4-wheel, agricultural tractor, 4...	2.23214 kg	18.32310	
> 05.33%	market for shed shed Cutoff, U - GLO	0.04983 m2	11.54366	
> 05.01%	market for transport, tractor and trailer, agricultur...	28.00000 t*km	10.86103	
> 04.98%	market for transport, tractor and trailer, agricultur...	28.00000 t*km	10.78957	
> 03.93%	market for electricity, low voltage electricity, low ...	28.00000 MJ	8.52269	0.00203

Figure 4.S. Carbon footprint for 1 ton of sisal fiber production in SC4.

● Impact category Climate change | Global warming potential (GWP100)

Contribution	Process	Required amount	Total result [kg C...	Direct contributi...
▼ 100.00%	Processing - SC4	1000.00000 kg	186.59374	
▼ 98.82%	Sun drying - SC4	1250.00000 kg	184.38503	
▼ 93.03%	Decortication - SC4	2600.00000 kg	173.59632	
▼ 87.21%	diesel-B100, burned in agricultural machinery die...	1440.12960 MJ	162.73428	1.17116
> 51.78%	esterification of soybean oil fatty acid methyl est...	32.00288 kg	96.62458	
> 18.79%	market for agricultural trailer agricultural trailer ...	5.21327 kg	35.05354	
> 09.82%	market for tractor, 4-wheel, agricultural tractor, 4...	2.23220 kg	18.32686	
> 06.19%	market for shed shed Cutoff, U - GLO	0.04983 m2	11.55813	
> 05.82%	market for transport, tractor and trailer, agricultur...	28.00000 t*km	10.86204	
> 05.78%	market for transport, tractor and trailer, agricultur...	28.00000 t*km	10.78871	
> 01.18%	market for electricity, low voltage electricity, low ...	28.00000 MJ	2.20871	0.00196

Cocoa (*Theobroma cacao* L.) Husk Potential for Biogas and Biofertilizer Production

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In the context of the transition to renewable energy sources, the valorization of agro-industrial waste is fundamental. Cocoa husk, in particular, emerges as a promising biomass, whose utilization can mitigate environmental impacts and foster a circular economy. The objective of this work is, therefore, to evaluate the potential of cocoa husk for the generation of biogas and biofertilizers. Despite technical challenges, such as its high moisture content, the conversion of this residue into energy can contribute significantly to the diversification of the national energy matrix. The research was conducted based on physicochemical analyses of samples collected in the municipality of Presidente Tancredo Neves - BA, covering parameters such as the determination of moisture content, total solids, volatile solids, ash, pH, cellulose, lignin, and heating value. This study contributes to the implementation of sustainable solutions and highlights the relevance of waste valorization in the transition to a clean energy matrix.

Keywords: Biomass. Cocoa Husk. Bioenergy. Characterization.

The increase in energy demand on a global scale, driven by both technological advancement and world population growth, has intensified the search for renewable and environmentally sustainable energy sources [1]. Still in the 21st century, the global energy matrix remains heavily dependent on fossil fuels, which contributes significantly to the worsening of global warming and climate change. In this scenario, the diversification of energy sources becomes strategic, with biogas being a promising alternative as it allows for the use of organic waste [2].

In Brazil, there is a variety of biomass with potential for energy conversion, such as corn husks, sugarcane bagasse, and rice straw. Specifically in the state of Bahia, the husk of the cocoa fruit stands out as a relevant resource in this context [2]. According to Mariatti and colleagues [3], this husk corresponds to about 76% of the total weight of the fruit, being the main residue generated in cocoa processing. Despite its wide availability, this

residue is often improperly discarded, which can result in negative impacts, such as the spread of agricultural diseases, for example, Witches' Broom and Brown Rot, in addition to soil imbalances due to its high potassium content [4].

Considering the urgency for complementary and renewable sources and the potential of this agricultural byproduct for the generation of biogas and biofertilizers, the objective of this work is to study the characteristics of cocoa husks to understand how they can be better used in the production of biogas and biofertilizers, seeking to show that, in addition to reducing environmental impacts, this residue can be transformed into a source of renewable energy and a useful product for agriculture.

Agro-industrial Residues

Agro-industrial residues are byproducts generated, for the most part, from the processing of food produced on a large scale. Among the main examples are bagasse, husks, seeds, and other organic materials discarded in large volumes. Despite often being treated as waste, these residues have a high potential for energy recovery [5].

Biomass from agricultural production has enormous potential to be converted into raw

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materials used in the production of biofuels, biopolymers, biomaterials, biofertilizers, and biopesticides. The use of this biomass, aligned with the principles of the bioeconomy, promotes environmental and social benefits, while at the same time boosting the economic sustainability of production chains [6].

Origin and Availability of Cocoa Husks

The cocoa tree (*Theobroma cacao* L.) is a perennial, tree-sized plant that develops well in shaded environments, such as undergrowth and sparse forests. Currently, the states of Bahia and Pará account for about 96% of the national production of cocoa beans, making them the main producing hubs in the country [7].

The cocoa tree varieties are grouped into three main types: Criollo, Forasteiro, and Trinitário, each with distinct characteristics regarding flavor, yield, and resistance [7].

According to the Brazilian Institute of Geography and Statistics (IBGE), in 2023 Brazil produced 296,145 tons of cocoa, of which 139,011 tons came from the state of Bahia, confirming its prominent position alongside Pará, which together account for a large part of the national production. It is estimated that approximately 236,916 tons correspond to cocoa husks, a high-volume residue with underutilized potential [8].

Historically, the husk has been discarded directly in the plantations or used as organic fertilizer. However, the improper disposal of the husk on the ground has contributed to the spread of fungi and diseases, representing a phytosanitary challenge in the plantations [9]. This situation has sparked scientific and technological interest in the search for alternative ways to utilize the cocoa husk, whether as an input for bioenergy, an agricultural substrate, or a raw material for compounds of higher added value.

Energetic Potential of Cocoa Husks

In the state of Bahia, cocoa cultivation stands

out as one of the main agricultural activities, generating a significant amount of byproducts. Among these residues, the husk of the cocoa fruit represents one of the largest volumes, yet it remains underutilized.

Both the husk and the cocoa bran have high potential for reuse and can be converted into energetic and agricultural inputs, such as biogas, biofertilizers, briquettes, and even substrates for the production of industrial enzymes.

The cocoa husk has physicochemical characteristics that qualify it as a promising biomass for energy purposes. Table 1 shows the energetic potential of various raw materials used as biomass, allowing for a comparison of the energy performance of cocoa husks with other sources.

The data indicate that cocoa husk has an amount of energy similar to that of sugarcane bagasse. Although it is lower than firewood, which has the highest value among the sources analyzed, cocoa husk presents itself as a viable and sustainable option, especially as it is a residue produced in large quantities and is seldom used.

Furthermore, the use of energy from biomass can help reduce dependence on fossil fuels, promote the use of renewable waste, and reinforce sustainability in cocoa production.

Materials and Methods

In this study, an experiment was conducted in triplicate with biomass samples from cocoa husks. The samples were collected from two distinct agricultural properties located in the municipality of Presidente Tancredo Neves - BA (13° 26' 56" S, 39°

Table 1. Higher Heating Value (HHV) of different biomass sources.

Raw Material	HHV (MJ/kg)
Firewood [10]	19.10
Cocoa husk [11]	16.23
Sugarcane bagasse [12]	18.04

25' 12" W). One of the collection areas corresponded to a cloned cocoa plantation (variety PS 1319), as illustrated in Figure 1, while the other was a common cocoa plantation (Forasteiro), represented in Figure 2.

After collection, the samples were properly stored and sent for analysis. The physicochemical and energetic characterizations of the biomass were carried out in two laboratories: at the Energy Laboratory (LEN) of the Federal University of Recôncavo da Bahia (UFRB) and at the Energy Laboratory at Senai Cimatec, in Salvador - BA. The sample preparation was performed based on the protocols recommended by the National Renewable Energy Laboratory (NREL), ensuring the standardization and reproducibility of subsequent analyses [13]. First, the samples underwent a size reduction and homogenization process; the fresh husks were manually cut into small particles using pruning shears.

Figure 1. Cloned cocoa in its natural state.



Figure 2. Common cocoa in its natural state.



Determination of Total Solids and Moisture Content

The determination of total solids and moisture content was performed in triplicate for both types of cocoa (cloned and common). Ten grams of biomass from each type were used, weighed on an analytical balance, and transferred to previously identified crucibles.

The samples were kept in a Limatec brand drying oven at a temperature of 105 ± 3 °C for a period of 18 hours. After this period, the crucibles were removed, cooled in a desiccator, and weighed to determine the dry mass. The ratio between the dry mass and the initial sample mass was used to calculate the total solids content (Equation 1). Moisture was calculated by the difference between the wet mass and the dry mass (Equation 2).

$$\text{Total solids content (\%)} = \frac{\text{Dry biomass mass}}{\text{Wet biomass mass}} \times 100 \quad (1)$$

$$\text{Moisture content (\%)} = 100 - \text{Total solids content} \quad (2)$$

Determination of the Heating Value

To calculate the Higher Heating Value (HHV), 10 g samples of each biomass type, which were previously ground and sieved through a 100-mesh screen, were sent to SENAI CIMATEC. The specialized technical team conducted the analysis using bomb calorimeters with heads, codes 3 and 4, in addition to an analytical balance, code 83823, and following the ASTM D240-19, DIN 51 900, and ASTM D5865 standards.

The Lower Heating Value (LHV) was determined from the HHV by subtracting the energy related to the vaporization of water produced during the combustion of the hydrogen contained in the sample. To find the hydrogen content, Equation 3 was used [14].

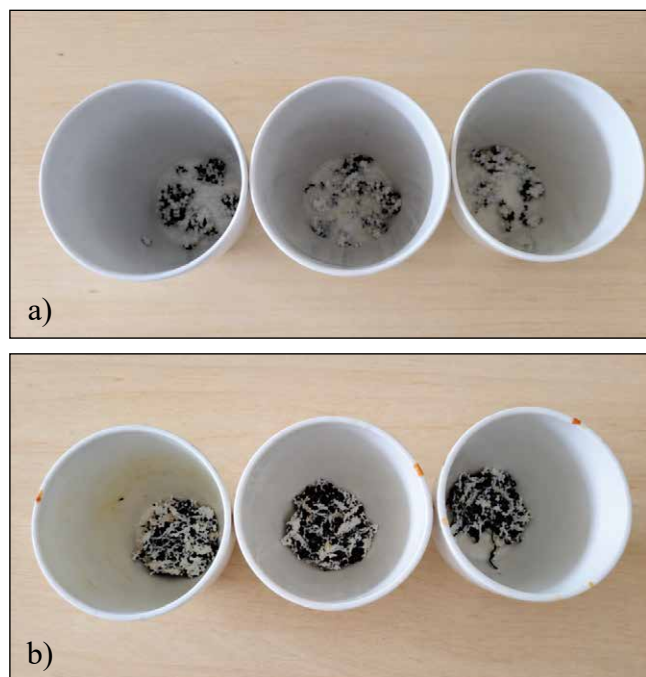
$$\%H = 10,72 + 2,43 \times \log_{10}(MV) \quad (3)$$

Determination of ash content

After the drying process in a Limatec brand drying oven at 105 ± 3 °C, the biomass samples

reached a constant mass and were then considered moisture-free, from which point the ash content could be calculated. For the determination of ash content, the dry samples were weighed in previously tared crucibles on an analytical balance and then subjected to incineration in a muffle furnace at 575 ± 25 °C for a period of 15 minutes (Figure 3).

Figure 3. Determination of ash content: biomass in crucibles after drying and incineration. a) Cloned cocoa husk and b) Common cocoa husk.



After this time, the crucibles were cooled in a desiccator and weighed again with the aid of an analytical balance. The ash content was calculated based on the difference between the mass of the dry sample and the residual mass after incineration.

Determination of Volatile Solids

To determine the volatile solids, it was necessary to calculate the difference between the dry mass of the biomass and the ash mass; for this, the raw material had been pre-treated and subjected to a muffle furnace at 575 °C. This content indicates the combustible organic compounds that turn into vapor during the sample's combustion process.

Determination of pH

To determine the pH, 10 g of the fresh sample were diluted in 100 mL of distilled water. The mixture was stirred and, after a resting period, the pH was measured using a calibrated pH meter.

Cellulose content

Three 1 g samples of dry biomass were prepared from each type of husk, and the material was transferred to a 250 mL Erlenmeyer flask. A 25 mL aliquot of a solution of nitric acid (90 mL) and glacial acetic acid (732 mL) was added, and the mixture was refluxed on a hot plate (MA 239 - Marconi) for 25 minutes at 120 °C. After cooling, the cellulose residue was vacuum-filtered through filter paper and washed with 500 mL of distilled water and 25 mL of ethanol. Subsequently, the material was dried in an oven at 100 ± 5 °C to a constant weight. After cooling in a desiccator, the filter paper containing the residue was weighed.

Results and Discussion

The results of this study allow for a comparison between the biomass of cloned cocoa husk (PS 1319) and common cocoa, highlighting their physicochemical properties and potential for energy use. The analyses performed included the determination of solids content, moisture, ash, heating value, and pH, providing essential information about the composition of this biomass and its implications for use as a biofuel. Taking into account the significant cocoa production in the Lower South region of Bahia, samples from this area were chosen for the research.

In the visual and gravimetric physical characterization of the cocoa samples, it was observed that the fruits of the cloned cocoa PS 1319 have a predominantly reddish color, a thicker husk, and a significantly higher mass of 520.74 g, when compared to the fruits of the common variety, which have a yellowish color, a thinner husk, and a

lower mass of 398.6 g. This difference indicates that the cloned cocoa has a greater volume and density, which can directly influence the yield of biomass originating from the husk. The physicochemical and energetic analyses of the cloned and common cocoa husk samples resulted in the average values presented in Tables 2 and 3.

It is noted that the moisture content was 83.13%, with a standard deviation of 0.53%, which demonstrates good consistency in the measurements. This high level of moisture is

Table 2. Average physicochemical and energetic properties of common cocoa husk.

Parameter	Common Cocoa	Standard Deviation
Moisture (%)	83.13	0.53
Total Solids (%)	16.87	0.53
Volatile Solids (%)	90.13	0.32
Ash (%)	10.03	0.32
HHV (MJ/kg)	17.45	0.26
LHV (MJ/kg)	14.05	-
Cellulose (%)	22.08	0.83
pH (%)	5.2	-

Table 3. Average physicochemical and energetic properties of cloned cocoa husk.

Parameter	Cloned Cocoa (PS 1319)	Standard Deviation
Moisture (%)	86.96	0.78
Total Solids (%)	13.04	0.78
Volatile Solids (%)	91.48	0.29
Ash (%)	8.68	0.29
HHV (MJ/kg)	17.03	0.12
LHV (MJ/kg)	13.63	-
Cellulose (%)	21.76	0.56
pH (%)	5.2	-

a determining factor, as it directly decreases the Lower Heating Value of the biomass and compromises combustion efficiency. Therefore, it is necessary to apply pre-treatment processes, such as drying, to enable its energetic use.

The total solids represented a percentage of 16.87%, of which 90.13% were volatile materials. This indicates that the biomass has a high potential to release combustible gases during the thermal process.

However, the ash content, which is 10.03%, may suggest an increase in the accumulation of solid residues after burning, which affects equipment maintenance and process efficiency.

The HHV was 17.45 MJ/kg, a value that is in line with other lignocellulosic biomasses. On the other hand, the Lower Heating Value was 14.05 MJ/kg, indicating a significant energy loss due to the high moisture content.

In addition to these parameters, the cellulose content found was 22.08%; its presence positively influences the heating value, as the thermal decomposition of cellulose releases combustible gases and contributes to the formation of char with high energy value.

However, since cocoa husk also has a high moisture content, part of this energy potential is compromised, reinforcing the need for pre-treatments to enable its use in processes such as direct combustion or gasification.

Table 3 presents the average results of the physicochemical analysis of the cloned cocoa husk, offering essential information to evaluate its viability as an energy source.

From the data presented in Table 3, it is observed that the moisture content was 86.96%, slightly above that recorded for the common cocoa husk. This indicates that the biomass was even more humid and, consequently, had more restrictions for direct energy use. The standard deviation of 0.78% indicates good consistency in the results among the analyzed samples.

The total solids content was only 13.04%, indicating a reduced amount of dry material available for combustion. Even so, the majority of

the dry material is composed of volatile substances (91.48%), indicating the possibility of releasing combustible gases during heating.

On the other hand, the ash content was 8.68%, slightly below that found in the common cocoa husk, which may indicate a lower production of solid residues after burning.

The Higher Heating Value was 17.03 MJ/kg, and the Lower Heating Value was 13.63 MJ/kg, demonstrating how the high moisture content negatively affects the energy efficiency of the biomass.

In the case of PS 1319, the cellulose content was 21.76%, a value very close to that found in the Forasteiro cocoa. This similarity indicates that, regardless of the variety, cocoa husk has a considerable cellulose content, which contributes to its potential as a lignocellulosic biomass.

Both biomasses have high levels of volatile solids, exceeding 90%, which suggests a high energy potential due to the release of combustible gases during combustion or thermochemical processes.

Both the Forasteiro and the PS 1319 cocoa husks presented a pH of 5.2, indicating a slightly acidic character. This value is relevant in the context of energy conversion, as pH can influence chemical stability, corrosivity, and microbial efficiency.

In the anaerobic digestion process, for example, the indicated pH for the activity of methanogenic microorganisms ranges between 6.7 and 7.5 [15]. Values below this range, such as the one obtained in this study, can compromise the yield of biogas production, requiring a prior pH correction through the addition of alkalizing agents.

Conclusion

This study highlights the energetic potential of cocoa husk, from both the common (Forasteiro) and cloned (PS 1319) varieties, as a renewable source of biomass. The physicochemical characterization revealed a high content of volatile solids in both samples, reinforcing their capacity to release combustible gases.

The PS 1319 variety stood out for its greater mass, favoring the energy yield per unit of volume and its use on an industrial or decentralized agro-energy scale. Despite the high moisture content, which reduces the LHV, this challenge can be overcome through pre-treatments such as drying. The pH indicates a need for alkalizing corrections for applications in biodigesters or biofertilizers.

In conclusion, cocoa husk is technically and energetically viable, with the potential to be integrated into waste valorization chains and to contribute to the environmental sustainability and economic development of producing regions.

Acknowledgment

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To the research group, BIORENEW, we wish our express gratitude for all support.

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Development of a 3D Model of a Prototype System for Geogas Capture Aiming at the Prospection of Light Hydrocarbons

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The prospection of light hydrocarbons in soils requires efficient systems for geogas capture; however, existing solutions often combine high cost, operational complexity, and low adaptability to variable field conditions. This study develops an innovative prototype to overcome these limitations, grounded in a critical analysis of patents that identified eight essential technical functions such as sealing against atmospheric contamination, clogging protection, and modular active collection. The methodology integrated a review of consolidated technologies (including Soil Gas Probe and Volatile Organic Compound Monitoring) with parametric CAD modeling, resulting in a modular system of six components interconnected by standardized threads. The design prioritizes constructive simplicity, enabling low-cost laboratory manufacturing, portability for remote areas, and adaptability to different depths and soil types. Compatible with analytical techniques such as gas chromatography via coupling with molecular filters, the prototype requires neither permanent infrastructure nor specialized consumables. Prepared for computational simulations of robustness and gas flow, the model ensures functional validation prior to physical prototyping, reducing risks and costs. As an intermediate solution between artisanal methods and complex industrial systems, it offers operational efficiency for small-scale geochemical prospection, with extended applications to environmental monitoring of VOCs and leak detection. It represents a strategic advance for national tools of sustainable exploration, with prospects for integration into in situ sensors and georeferenced mapping platforms.

Keywords: Geogas Capture. Modular Prototype. Hydrocarbon Prospection.

The patent literature review reveals a vast and diverse range of solutions for interacting with soil gases. At one extreme are highly complex systems for the active extraction of hydrocarbons, which employ technologies such as ultrasonic fracturing of geological formations to release the target compounds [1]. However, for geochemical prospection, the focus lies on sampling and analyzing gases already present in the soil.

Within sampling, approaches can be fundamentally divided into two types. The first is advective (active) sampling, in which soil gas is actively drawn by vacuum into the probe, with designs prioritizing the purging of atmospheric contaminants through valves to ensure sample integrity [2]. The second is diffusive (passive) sampling, which seeks to minimize soil disturbance;

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in these systems, a gas-permeable membrane allows the target compounds to equilibrate with a closed-loop analysis circuit, without the need for vacuum extraction [3].

Detection sensitivity is another point of innovation, with devices focused on pre-concentrating the sample using molecular sieves and adsorbent materials to capture and concentrate light hydrocarbons, which are later thermally desorbed in the laboratory for chromatographic analysis [4]. The robustness and field functionality of the probe are also the subject of specific developments, with optimizations in the mechanical design of the probe tip to prevent clogging of the sampling pathways by soil particles [5]. Finally, the integration of the sampler into a broader system is explored in solutions that propose semi-permanent monitoring ports for periodic evaluations [6] or mobile systems that couple sampling to GPS units for real-time mapping of gas concentrations [7].

Despite the diversity of solutions, the combined analysis of these documents reveals a gap in models

that integrate constructive simplicity, low cost, operational efficiency for active collection, and adaptability to different field conditions, without relying on complex consumables or permanent installations. In light of this, the present work proposes the development of a three-dimensional model of a prototype system for geogas capture, designed in a CAD (Computer-Aided Design) environment, which may later be manufactured and validated through experimental testing and computational simulations.

Materials and Methods

The methodology adopted was based on three main stages: analysis of patent documents, selection of technical features, and CAD modeling of the equipment components.

Initially, a search and comparative study of patents related to soil gas capture and geochemical sampling was carried out. This analysis focused on identifying well-established solutions, their strengths, and limitations, in order to support design decisions better suited to the intended application.

Based on the collected data, a set of priority features for the model was defined, such as structural robustness, ease of assembly and disassembly, feasibility of laboratory manufacturing, and compatibility with sensors and filtration elements. With these premises in mind, six main parts were designed, all modeled in Solid Edge, respecting dimensions and shapes compatible with the technical requirements of the application.

The development of the prototype system for geogas capture was conducted in a three-dimensional modeling environment using Solid Edge software.

Throughout the modeling process, parametric tools and extrusion, revolution, and cutting operations were used to define the geometries. The final assembly was visually validated for fit and functional coherence and prepared for future analysis through structural and flow simulations in Solid Edge, to be evaluated using the NX Nastran environment.

Results

From the patent analysis, it was possible to identify the following functions, with their respective characteristics presented in Table 1.

As a result of the modeling stage, a complete three-dimensional assembly was obtained, composed of six distinct parts that, once assembled, form the prototype system for geogas capture. Each part performs a specific function in the process of capturing, directing, and storing gases extracted from the soil.

Figure 1 shows the isometric views of all components that make up the prototype, numbered from 1 to 6. Elements 1 and 2 are joined by welding, forming the interface with the operator and remaining positioned externally to the soil. The lower end of element 2 is threaded to element 3, which acts as an extension piece, allowing the equipment's depth to be increased, and connects to element 4 also by threading.

Element 4 is the central part of the equipment, responsible for direct interaction with the soil. Through multiple holes distributed along its surface, the geogas enters the system's interior. Inside it, element 6 is housed, serving as a support for the dust-proof mesh and the molecular sieve.

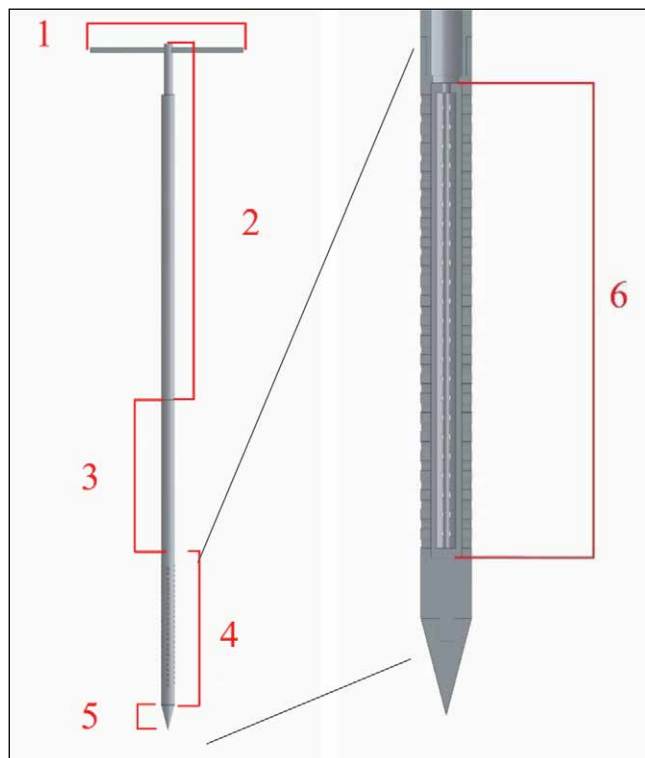
At the bottom, element 4 is threaded to element 5, which corresponds to the drilling tip. Since it is threaded, this tip can be replaced according to the project's requirements.

Discussion

The comparative analysis of the patents indicated a wide variety of solutions for soil gas collection and analysis, ranging from simple manual insertion systems to complex devices integrating sensors and pre-concentration modules. Recurring functions such as probe drilling and insertion, access point sealing, and clogging protection appear in multiple records, reflecting their importance in ensuring sample integrity and process efficiency. Other functions, such as in situ gas analysis and periodic monitoring, highlight

Table 1. Functions and characteristics of the analyzed patents.

Function	Technical Characteristics	Related Patents
Probe drilling and insertion	Insertion by impact, hydraulic pressure, or manually; conical or retractable tips; use of guide tube (drive tube) to protect the assembly; typical diameter 1–3 cm.	• Volatile Organic Compound Monitoring • Vapor Probe for Soil Gas Vapor Sampler • Soil Gas Probe • Geochemical Soil Sampling for Oil and Gas Exploration
Access point sealing	Sealing with VOC-resistant epoxy or sealants; use of one-way valve or Swagelok fitting system; prevents entry of surface air.	• Volatile Organic Compound Monitoring • Soil Gas Probe
Clogging protection	Stainless steel mesh, flexible disks, or “umbrella” to prevent soil particles from blocking inlets; physical protection for collection holes.	• Vapor Probe for Soil Gas Vapor Sampler • Apparatus and Method for Measuring Soil Gases
Soil gas collection	Intake through gas-permeable membranes, side holes, or slots; conduction via tube to the surface; sampling with pump, vacuum, or carrier gas circulation.	• Apparatus and Method for Measuring Soil Gases • Geochemical Soil Sampling for Oil and Gas Exploration • Soil Gas Probe • Volatile Organic Compound Monitoring
Sample concentration and preservation	Use of collector tubes with molecular sieves; selective adsorption; transport for laboratory analysis.	• Geochemical Soil Sampling for Oil and Gas Exploration
In situ gas analysis	Probe coupled to sensor and datalogger; closed-loop circulation with carrier gas; continuous measurement of concentration and diffusivity.	• Apparatus and Method for Measuring Soil Gases
Purging prior to collection	Connection of an evacuated container to remove residual gases from the probe before collecting the sample.	• Soil Gas Probe • Volatile Organic Compound Monitoring
Periodic monitoring and recording	Scheduled collections; recording in a database; comparison with historical data; risk assessment and mitigation needs	• Volatile Organic Compound Monitoring
Environmental and industrial applications	Hydrocarbon prospection, leak detection in underground tanks, monitoring of VOCs and greenhouse gases.	• All analyzed patents

Figure 1. Equipment assembled with all the parts.

automation trends and integration with analytical systems, especially for continuous industrial and environmental applications.

From Table 1, it can be observed that patents such as Volatile Organic Compound Monitoring and Soil Gas Probe prioritize contamination control and sample collection repeatability, while solutions like Geochemical Soil Sampling for Oil and Gas Exploration and Apparatus and Method for Measuring Soil Gases explore pre-concentration techniques and direct measurements. Despite their robustness and technical efficiency, many of these solutions involve high manufacturing costs, the use of specialized consumables, or the need for permanent installation, which may limit their applicability in small-scale exploratory campaigns or remote regions.

The prototype developed in this work incorporates essential functions identified in the analyzed patents but adapts them to a modular, portable, and low-cost format, prioritizing constructive simplicity and ease of assembly and maintenance. Elements such as the

threaded tip (element 5) and the dust-mesh holder (element 6) replicate sealing and filtering principles found in consolidated models but were redesigned for compatibility with laboratory manufacturing and operation in different soil types.

Furthermore, the simplified geometry and use of standardized threads allow the coupling of extensions (element 3) for different sampling depths, meeting the adaptability requirement identified in the patent literature. Compatibility with filters and molecular sieves enables future integration with analysis systems such as gas chromatography, aligning with trends in qualitative and quantitative measurements of light hydrocarbons.

Finally, preparing the model for simulations in NX Nastran represents a methodological advantage, allowing prediction of structural and functional performance before physical construction, thereby reducing risks and costs in the prototyping process. Thus, this development positions itself as an intermediate solution between artisanal models and highly specialized systems, offering versatility for applications in geochemical prospecting, environmental monitoring, and exploratory research.

The parts were modeled to allow simple assembly without the need for complex tools. Their geometries were adjusted to ensure sealing and mechanical integrity, enabling subsequent use in experimental gas collection under real field conditions. The model is also ready to be computationally analyzed for structural and performance validation.

From the analysis of existing patents in the field of soil gas capture, it was possible to observe a diversity of technical solutions, varying in terms of constructive complexity, materials used, and integration with analytical systems. However, many of the models found presented limitations related to portability, manufacturing cost, and adaptability to different soil types and sampling depths.

The model developed in this work seeks to address some of these gaps by incorporating

a modular approach, composed of parts with simplified and functional geometry. The use of Solid Edge as a modeling tool made it possible to explore different configurations until reaching an optimized set of parts that meet the defined technical requirements, with a focus on practical feasibility.

In addition, the proposal stands out for considering, from its conception, compatibility with analysis systems such as gas chromatography, by allowing the coupling of filters and sensors. Another relevant point is the preparation for future simulations in the NX Nastran environment, which will make it possible to evaluate the structural and functional behavior of the system before its fabrication.

Thus, this work advances toward providing a solid basis for the construction of devices applicable in geochemical prospecting campaigns, particularly aimed at identifying light hydrocarbons in terrestrial environments.

Conclusion

The development of the three-dimensional model of a prototype system for geogas capture, presented in this work, was grounded in a detailed review of relevant patents in the field of geochemical sampling. This analysis made it possible to identify essential functions such as drilling and probe insertion, efficient sealing, clogging protection, and active gas collection, as well as features associated with pre-concentration, in situ analysis, and periodic monitoring.

By incorporating these functions in an adapted manner, the prototype stands out for its modularity, constructive simplicity, and portability — aspects rarely explored in consolidated commercial solutions. The use of threaded components, optimized geometries, and compatibility with different soil types provides flexibility for application in exploratory campaigns for light

hydrocarbons, without requiring permanent infrastructure or high-cost consumables.

In addition, compatibility with filters and molecular sieves broadens the potential for integration with analytical techniques such as gas chromatography, while preparing the model for simulations in NX Nastran ensures a structural and functional validation stage prior to physical fabrication, minimizing risks and costs.

Thus, the proposed prototype represents a strategic advance in the development of national tools for geochemical prospecting, combining operational efficiency, economic feasibility, and adaptability. Its future application could meet not only exploratory demands in the oil and gas sector, but also environmental monitoring and scientific research in diverse geological contexts.

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Estimation of the Spatiotemporal Distribution of Soil Carbon Fluxes in the Conceição do Coité Region (Bahia, Brazil) Using Remote Sensing Data

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As climate change worsens, it is essential to seek efficient climate monitoring strategies and develop low-cost, broad-coverage models to assess carbon dioxide (CO₂) fluxes in semiarid ecosystems. This study proposed to estimate the spatiotemporal dynamics of carbon flux (CO₂flux) in soils of the semiarid region, in the municipality of Conceição do Coité (Bahia, Brazil), between 2020 and 2024. Data from Sentinel-2 satellite images were used, processed in Google Earth Engine, integrating the NDVI and PRI indices. The data were evaluated in two climatic periods: rainy period (RP) and dry period (DP). Overall, the average soil carbon flux indices between each climatic period, across the years studied, were 0.172 for RP and 0.112 for DP. The results revealed that CO₂flux is directly related to the rainfall regime, with higher values in wetter years, such as 2021, and a significant drop in 2023 and 2024. The Caatinga vegetation responded positively to the rainfall, resulting in higher rates of carbon sequestration in areas with vegetation cover. Adapted to the conditions of the semi-arid climate, the cultivation of *Agave sisalana*, widespread in the studied region, has the potential to contribute to the reduction of greenhouse gas emissions and the recovery of degraded areas. The study also showed that remote sensing data can be considered a low-cost strategic tool for environmental monitoring associated with CO₂ fluxes in soils and for the implementation of actions aligned with the Sustainable Development Goals (SDGs). In the context of the current climate crisis, reduced carbon flux in water deficit scenarios may contribute to a decrease in the carbon sink potential of soils, weakening their role as a climate regulator.

Keywords: *Agave sisalana*. Caatinga. Carbon Flux. Remote Sensing. Semi-Arid.

Abbreviations: NDVI, Normalized Difference Vegetation Index. PRI, Photochemical Reflectance Index. CO₂Flux, Carbon Sequestration Index. GEE, Google Earth Engine. RP, Rainy Period. DP, Dry Period.

The growing interest in carbon (C) dynamics in arid and semiarid zones stems from recent evidence pointing to significant changes in the stock of this chemical element in the soil, associated with climate change and intensive land use in these regions [1-3]. In Brazil, the semiarid region represents almost 11% of the national territory and 76% of the Northeast region. It is a region traditionally prone to droughts, which has faced an intensification of desertification and soil erosion, driven by anthropic actions, combined with edaphoclimatic conditions [4,5]. The caatinga, the predominant vegetation of the

semiarid region, has a unique biodiversity among seasonally dry tropical forests (SDTF), being an ecosystem that has characteristics of both tropical forests and seasonally dry areas [6]. With a total area of 912,529 km², it is considered the largest SDTF in the world, which reinforces its ecological importance [7].

The historical process of occupation of the territory belonging to the Caatinga has drastically altered its original coverage, where only 11.04% of the Caatinga area currently retains natural vegetation, and only 4.34% remains as forest cover, where 1.3% has full protection (Full Protection Conservation Units) and 6.2% are Sustainable Use Conservation Units [7,8]. There are numerous consequences generated by high population density and anthropic activities of predatory models in the Caatinga [9,10]. Anthropic actions such as deforestation, intensive land use, and biomass burning directly interfere with the

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carbon cycle, an essential chemical element for terrestrial ecosystems [11].

In this cycle, carbon dioxide (CO₂) and water vapor are absorbed by plants through the process of photosynthesis. Solar energy is converted into organic compounds rich in carbon, which is stored in the different parts of the plant, transferring C from the atmosphere to the biosphere and, consequently, this chemical element is transferred to the soil, contributing to carbon stocks below the surface [12,13]. It is worth noting that in 2023, the terrestrial carbon sink absorbed only 0.44 Gt C, compared to the average of 2.6 Gt C/year in the previous decade. This decline was associated with extreme drought and heat events that led to weakened CO₂ absorption, reduced net photosynthesis, and increased emissions from burning and decomposition of organic matter [14].

In this sense, remote sensing has consolidated itself as a fundamental tool for investigating the terrestrial carbon cycle, allowing both the quantification of carbon fluxes and stocks in ecosystems [15], and the assessment of the impacts of global changes on carbon dynamics [16,17]. In this context, spectral indices such as NDVI (Normalized Difference Vegetation Index) [18] and PRI (Photochemical Reflectance Index) [19] have stood out as fundamental tools for monitoring vegetation dynamics. The integration between these two indices allows the derivation of a new parameter, known as CO₂ flux, which is related to carbon sequestration, by quantifying photosynthetically active vegetation in a study area.

Thus, this study aimed to estimate the spatiotemporal distribution of CO₂ flux based on multispectral remote sensing data in the region of the municipality of Conceição do Coité (Bahia, Brazil), which encompasses a considerable area of semiarid climate and Caatinga vegetation, in the Northeast region. The work was carried out in a semiarid municipality characterized by a high rate of cultivation of *Agave sisalana*, a plant widely used in fiber production. Agave species have great

potential for biomass expansion as a source of bioenergy in future climate scenarios, especially in semiarid agricultural lands that present some degree of degradation or are categorized as unsuitable [20]. Therefore, this work reinforces the relevance of studies aimed at monitoring carbon fluxes and environmental conditions in these regions, since such crops can play a strategic role in the recovery of degraded areas and in mitigating CO₂ emissions [21,22].

Materials and Methods

Area of Study

This study evaluated the spatiotemporal distribution of CO₂ flux in soils in the municipality of Conceição do Coité, located approximately 210 km from the capital of Bahia state, Salvador. The municipality is part of the Sisal Territory, which is composed of 20 municipalities and covers an area of 20,454.29 km². Agriculture is the predominant activity in this region, with *Agave sisalana* being the main agricultural crop, aimed at the export of its fiber [23].

The municipality is located in the Northeast Semi-arid region, which has a BSh climate classification (hot semi-arid), with high average temperatures (25 °C to 30 °C) and precipitation between 400 and 1200 mm per year, with two distinct seasons during the year: a rainy season and a dry season, with an irregular rainfall regime during the years [24]. The main characteristic of the semiarid rainfall regime is the irregularity in the temporal and spatial distribution of precipitations [25,26].

The predominant vegetation in the region corresponds to the Caatinga biome [7], which is adapted to reduced precipitation and high temperatures and evapotranspiration [27,28], adjusting its physiological mechanisms to improve the efficiency of water use and carbon fixation, so that changes in plant phenology are reflected in the dynamics of carbon exchange between the biosphere and the atmosphere [29,10].

Obtaining Remote Sensing Data

The scenes chosen for the spatiotemporal estimation of carbon fluxes in soils in the studied region refer to the rainy period (RP) (months from November to May) and the dry period (DP) (months from June to October), from 2020 to 2024. These scenes were acquired and processed free of charge through Google Earth Engine (GEE), using Sentinel-2 satellite images from the MSI sensor. For the spatialization of the spectral indices, a regular vector grid with a spatial resolution of 25 km² (5 km × 5 km) was generated, covering the entire extent of the study area. This grid was used as a basis for the extraction and statistical aggregation (average) of the spectral values of the dry and rainy periods, allowing a comparative evaluation between the years and the mapping of intra-annual variability.

We chose to use images from the Sentinel-2 satellite due to their high spatial resolution. The images were acquired at processing level 2A, meaning they were already atmospherically corrected using the Sen2Cor processor, which eliminates interference caused by aerosols and water vapor [30]. On the Google Earth Engine (GEE) platform, these images are made available as “Surface Reflectance”, eliminating the need for additional atmospheric correction. This ensures greater precision in the extraction of spectral indices, such as NDVI, in areas of vegetation with seasonal variation, such as the Caatinga.

Spectral Indices of Carbon Flux

To estimate CO₂ fluxes in the studied area, after obtaining remote sensing data, the Forest Carbon Sequestration Index (CO₂flux), initially proposed by Rahman (2001) [31], was used, which integrates the NDVI and PRI indices into a single carbon sequestration metric. The NDVI was calculated using the reflectance of the red and near-infrared bands with a central wavelength of 665 nm (RED) and 842 nm (NIR) (Equation 1).

$$NDVI = \left(\frac{R_{NIR} - R_{RED}}{R_{NIR} + R_{RED}} \right) \quad (1)$$

where R is the reflectance of the wavelengths of the near infrared (NIR) and red (RED) bands.

The PRI was also calculated, which reflects the photosynthetic efficiency of vegetation from the blue and green bands. To calculate the PRI, the ratio of bands corresponding to the central wavelength 490 nm (blue) and 560 nm (green) was considered, with the absorption of the blue band in relation to the peak occurring in the green reflection band [32], ranging from -1 to +1 (Equation 2).

$$PRI = \left(\frac{R_{blue} - R_{green}}{R_{blue} + R_{green}} \right) \quad (2)$$

where R is the reflectance of the wavelengths of the respective bands.

To adapt the PRI to the model, a scaling was applied to make it positive (sPRI; Equation 3), as proposed by Rahman and colleagues (2001) [31], improving the correlation with net primary production.

$$sPRI = \frac{(PRI + 1)}{2} \quad (3)$$

The CO₂flux estimate (Equation 4) results from the relationship between the NDVI and sPRI values, measuring the efficiency of carbon sequestration by vegetation, with its result expressed in the range between -1 and +1.

$$CO_2flux = NDVI \times sPRI \quad (4)$$

The CO₂flux index was used as a dimensionless and proportional measure of carbon flux, as it is derived from the NDVI and PRI indices [32]. To obtain quantitative values of the CO₂flux index expressed in μmol m⁻² s⁻¹, it would be necessary to use data from micrometeorological towers, performing a regression between the real CO₂ fluxes and the values estimated by the index, as proposed by Silva & Baptista (2015) [33].

Finally, the values were subjected to descriptive statistical analysis (including mean, standard deviation and percentage of valid data), according to approaches used in studies based on orbital data and without in situ validation [34].

Results and Discussion

The estimated values for soil carbon flux indices between RP and DP are presented in Table 1.

High levels of soil carbon flux during dry periods may be associated with the presence of organic matter in the soil and occasional significant rainfall (as observed in 2021, where soil carbon flux remained high during both periods, DP and RP). Soil carbon flux is directly associated with soil respiration, organic matter decomposition, and microbial activity, and is influenced by factors such as humidity, temperature, and rainfall

dynamics [10, 26]. Therefore, Figure 1 shows the annual precipitation rates for the municipality of Conceição do Coité, for the years 2020 to 2024, during the dry (DP) and rainy (RP) periods.

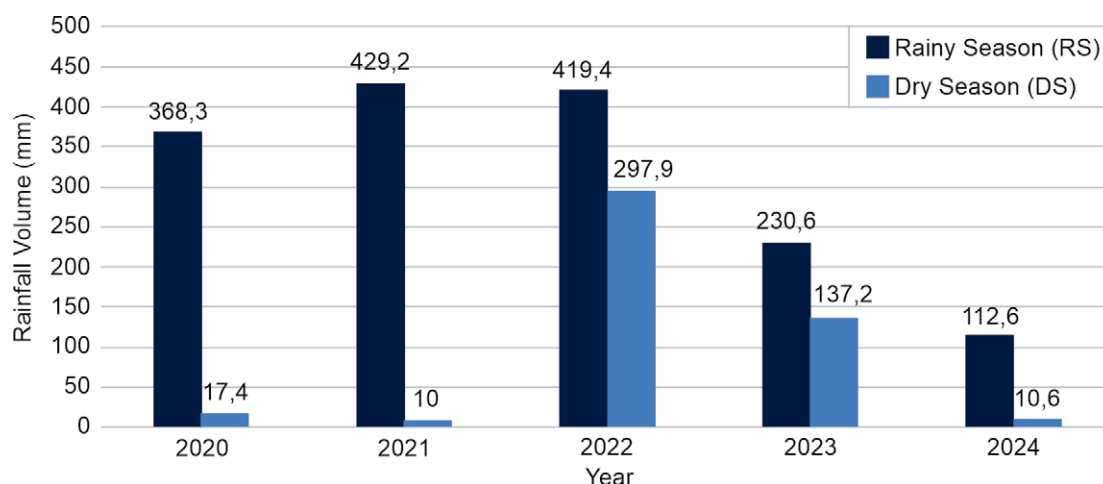
It can be observed that, during this period, there was great seasonal variability in the rainfall regime, with averages varying between 94 mm (DP) and 312 mm (RP). Studies on the homogeneous rainfall zones in Bahia indicate that precipitation in the semi-arid region of this state is strongly conditioned by different meteorological systems such as Frontal Systems, the South Atlantic Convergence Zone and Cyclonic Vortices, which

Table 1. Estimates of soil carbon flux over different climatic periods (2020–2024).

Year	Rainy period		Dry period	
	Minimum	Maximum	Minimum	Maximum
2020	0.074	0.265	0.031	0.249
2021	0.027	0.236	0.094	0.308
2022	0.039	0.257	0.068	0.220
2023	0.068	0.232	0.042	0.144
2024	0.068	0.255	0.052	0.195
Range	0.027 - 0.265		0.031 - 0.308	
Mean $\pm$ SD*	0.172 $\pm$ 0.051		0.112 $\pm$ 0.071	

*SD = standard deviation.

Figure 1. Average rainfall volume (mm), between 2020 and 2024, Divided by rainy (RP) and dry (DP) periods for the Conceição do Coité Region, Bahia, Brazil.



Source: National Institute of Meteorology (2025) [37].

promote rainfall between November and April, peaking in December, with averages of 127 mm (DP) and 544 mm (RP) [36].

The complex interaction between rainfall seasonality and carbon exchange in the Caatinga suggests that seasonal climate change plays a crucial role in modulating carbon fixation rates in this ecosystem [26].

Carbon flux spectral index (CO₂Flux) maps demonstrated a clear correlation between rainfall patterns and soil-atmosphere carbon exchange dynamics (Figure 2).

The values for the indices presented range from <0.0279 (dark red tones, indicating very low flux) to values >0.3082 (bluish tones, corresponding to the highest estimated flux level). Baptista (2004) [35] mentions that the greater the photosynthetic activity, the greater the effectiveness of the carbon sequestration process, and thus, the greater the spectral index.

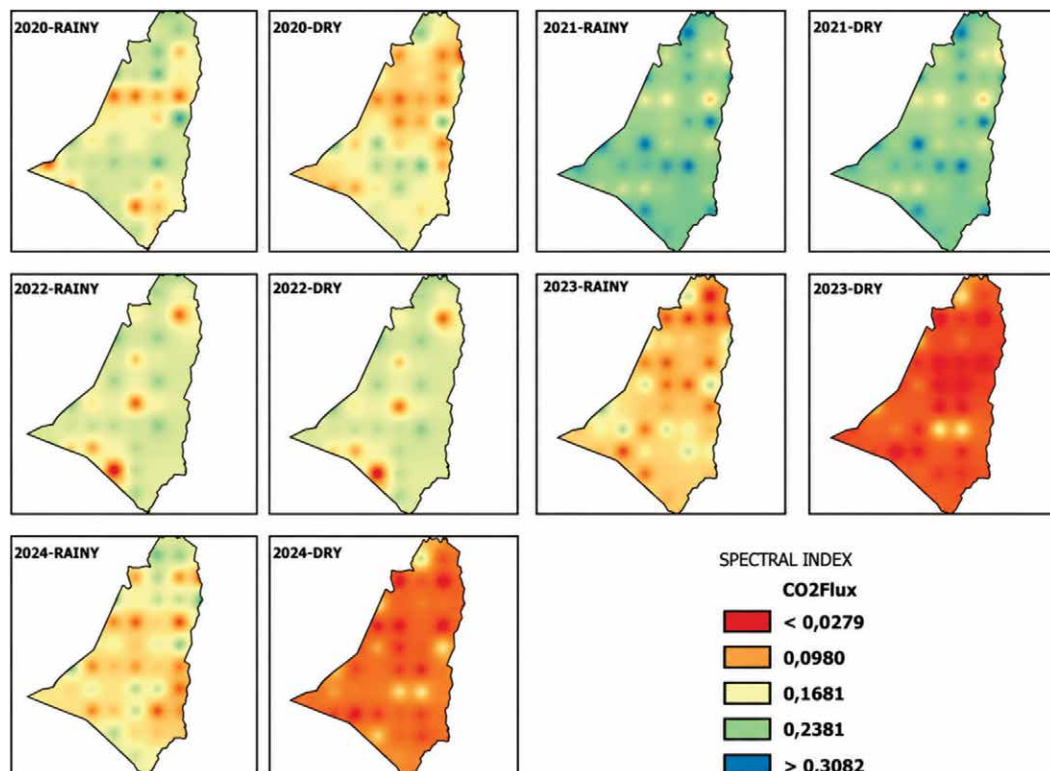
It was observed that, in the years 2023 and 2024, especially during dry periods, there was a significant

reduction in soil carbon flux, with minimum spectral index values concentrating below 0.0980. This trend followed the significant drop in precipitation recorded in these years, with emphasis on the rainy season of 2024, which recorded only 112 mm, compared to 230 mm in 2023, which may highlight the impact of water restriction on plant activity and soil respiration. Another factor that can affect carbon sequestration, and may have influenced local indices, is deforestation.

The Caatinga biome faces increasing anthropic pressures, being among the three most deforested in the country in 2023, which highlights the serious threat to its environmental balance. That year, the state of Bahia was responsible for 93,437 hectares of native vegetation lost, representing a 34% increase compared to 2022 [7].

Silva Junior (2020) [38] verified that, in regions where there is an increase in deforestation, changes in the configuration of vegetation cover are observed, resulting in direct carbon losses. Additionally, the reduction in relative humidity

Figure 2. Carbon flux maps between 2020 and 2024 in the respective rainy and dry periods.



compromises processes such as the decomposition of organic matter and microbial activity, which are fundamental for the flow of carbon in the soil.

Understanding the dynamics of carbon flow in the environment can contribute to the assessment and management of environmental resources in relation to land use. Furthermore, it can provide support for assessing the consequences of the current climate crisis, contributing to the adoption of practices aimed at combating desertification and restoring degraded lands, in accordance with the UN Sustainable Development Goals (SDGs) (especially SDGs 13 and 15).

Conclusions

Soil carbon flux was shown to be sensitive to hydric regime variability, with marked responses to climatic seasonality.

In the context of the current climate crisis, in which rainfall variations have become more intense, irregular, and unpredictable (especially in semiarid regions), the results demonstrated that the reduction in carbon flux in water deficit scenarios can contribute to the reduction of the carbon sink potential of soils, weakening their function as climate regulators.

The use of strategic tools such as remote sensing has proven to be efficient in environmental monitoring and in planning actions aimed at sustainability, especially in regions that suffer the severe effects of variations in climatic conditions. Implementing these tools reduces the costs of continuous soil monitoring, making it more accessible, and enabling an understanding of seasonal variations and the effects of different management practices.

To achieve this, it is essential to define clear metrics or local indicators, such as carbon stocks, seasonal fluxes, moisture indices, and vegetation cover. Integrating these data with national inventories, following internationally recognized methodologies (IPCC), ensures that the results support climate mitigation policies and sustainable soil management strategies.

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Experimental Characterization of Macrobending Fiber Sensor Coupled via Vibrating Membrane for Acoustic Detection

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This work investigates the application of a fiber-optic acoustic sensor based on macrobending loss for gas leakage detection, employing a membrane-coupled architecture to enhance acoustic sensitivity and directional selectivity. The proposed system integrates a single-mode fiber coiled inside a cylindrical structure sealed with thin membranes, which act as mechanical transducers by converting acoustic waves into localized perturbations along the fiber curvature. The experiments were conducted to evaluate the sensor's response under controlled excitation conditions, varying frequency, sound pressure level, source distance, and angular orientation. Results demonstrate that tighter curvature yields significantly higher optical attenuation. Spatial sensitivity was characterized by a nonlinear increase in attenuation with distance, and directional behavior was confirmed by enhanced attenuation under oblique wave incidence. The practical applications of the findings are diverse, with particular emphasis on gas leak monitoring in industrial settings.

Keywords: Acoustic Sensor. Macrobending Loss. Leak Detection. Acoustic Identification. Fiber Optic Sensor.

Abbreviations: DAS, Distributed Acoustic Sensing. FBG, Fiber Bragg Grating. FFT, Fast Fourier Transform.

Detection and characterization of low-intensity vibration pose significant challenges across various scientific and engineering disciplines due to fluid flow's inherently chaotic and irregular nature. The advancement of acoustic sensing technologies is crucial for accurately capturing and quantifying these phenomena.

Optical fibers are recognized not only as the backbone of high-speed telecommunications but also as a versatile platform for advanced sensing applications. Their inherent properties, such as low attenuation, electromagnetic immunity, and high sensitivity, make them ideal candidates for structural health monitoring, environmental surveillance, and chemical or acoustic detection in harsh environments [1]. Distributed sensors, such as Distributed Acoustic Sensing (DAS), enable the detection of vibrations along extensive lengths of fiber, facilitating the identification of gas leaks in both urban and underground pipelines [2-4].

Interferometric techniques, such as Fabry-Perot [5] and Mach-Zehnder [6] have shown promising results, offering broad frequency response under adverse conditions. Fiber Bragg Grating (FBG) acoustic sensors have also demonstrated high sensitivity in detecting ultrasonic waves [7,8]. However, these methods have certain limitations: they are primarily viable for new pipeline installations, require the integration of fiber throughout the pipeline network, are most effective for monitoring large leaks, demand sophisticated interrogation systems, and tend to be costly. Fiber optic sensors based on macrobending, intentionally inducing curvature in the optical fiber to cause light leakage, have emerged as a powerful technique for detecting mechanical perturbations, particularly acoustic vibrations. Traditionally viewed as a loss mechanism in telecommunications, macrobending can be harnessed to transduce acoustic or vibrational energy into measurable variations in optical power [9,10]. When external acoustic fields induce dynamic strain on the bent section of the fiber, the resulting modulation in bending radius leads to variations in optical attenuation, which can be directly correlated with the incident acoustic signal.

Distributed sensors, such as Distributed Acoustic Sensing (DAS), enable the detection

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of vibrations along extensive lengths of fiber, facilitating the identification of gas leaks in both urban and underground pipelines [2-4]. Interferometric techniques, such as Fabry-Perot [5] and Mach-Zehnder [6] have shown promising results, offering broad frequency response under adverse conditions. Fiber Bragg Grating (FBG) acoustic sensors have also demonstrated high sensitivity in detecting ultrasonic waves [7,8]. However, these methods have certain limitations: they are primarily viable for new pipeline installations, require the integration of fiber throughout the pipeline network, are most effective for monitoring large leaks, demand sophisticated interrogation systems, and tend to be costly. Fiber optic sensors based on macrobending, intentionally inducing curvature in the optical fiber to cause light leakage, have emerged as a powerful technique for detecting mechanical perturbations, particularly acoustic vibrations. Traditionally viewed as a loss mechanism in telecommunications, macrobending can be harnessed to transduce acoustic or vibrational energy into measurable variations in optical power [9,10]. When external acoustic fields induce dynamic strain on the bent section of the fiber, the resulting modulation in bending radius leads to variations in optical attenuation, which can be directly correlated with the incident acoustic signal.

Fiber optic sensors based on macrobending, intentionally inducing curvature in the optical fiber to cause light leakage, have emerged as a powerful technique for detecting mechanical perturbations, particularly acoustic vibrations. Traditionally viewed as a loss mechanism in telecommunications, macrobending can be harnessed to transduce acoustic or vibrational energy into measurable variations in optical power [9,10]. When external acoustic fields induce dynamic strain on the bent section of the fiber, the resulting modulation in bending radius leads to variations in optical attenuation, which can be directly correlated with the incident acoustic signal.

The present study explores the application of this macrobending phenomenon to develop an

acoustic sensor aimed at detecting characteristic frequency signals associated with gas leaks in pipelines. This approach offers key advantages: passive and electrically safe operation in flammable or hazardous environments, robustness against electromagnetic interference, and the potential for a cost-effective solution. Specifically, the aim is to investigate the correlation between sound-induced optical attenuation and spatial parameters (e.g., coil diameter and excitation distance), and to assess the sensor's feasibility for gas leak detection applications.

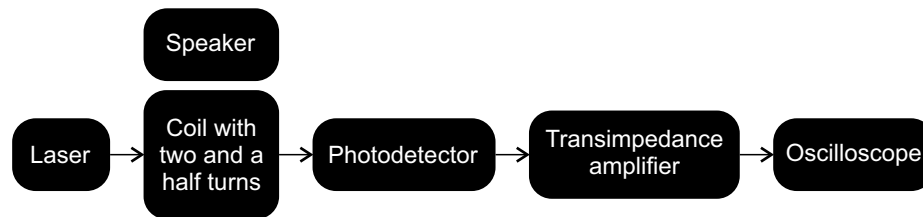
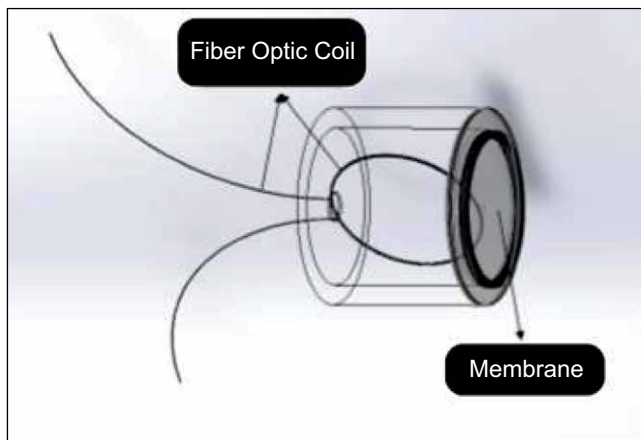
Materials and Methods

Figure 1 illustrates the schematic diagram of the experiment setup that comprised a 1550 nm laser, a Corning SMF-28e+ optical fiber, a speaker, a photodetector, a transimpedance amplifier, and an oscilloscope. The optical fiber was connected to the laser source and passed through the tube containing the coiled section. At the output, the fiber was connected to a photodetector that converted optical power fluctuations into an electrical current. This current was subsequently amplified by a transimpedance amplifier and monitored using an oscilloscope for temporal analysis.

The sensing head was composed of a 2.5-turn fiber coil enclosed within a cylindrical tube measuring 25.4 mm in diameter and 35.0 mm in length. To investigate the influence of curvature-induced loss, three different coil diameters were tested: 15 mm, 20 mm, and 25 mm.

As depicted in Figure 2, both ends of the tube were sealed with thin membranes fabricated via 3D printing, designed with micro-apertures to permit fiber insertion. A segment of the coiled fiber maintained direct contact with the internal surface of the diaphragm, enabling efficient transmission of acoustic-induced displacements.

Acoustic excitation was applied using a commercially available speaker placed externally in front of the sensor head. The system was evaluated under both single-tone and dual-tone

Figure 1. Experiment setup.**Figure 2.** Schematic representation of the sensor head.

excitation protocols. In the single-frequency mode, isolated sinusoidal signals of 200 Hz, 440 Hz, and 500 Hz were applied individually. In the dual-frequency mode, simultaneous tones of 320 Hz and 325 Hz were employed to investigate the sensor's resolution in distinguishing closely spaced spectral features.

The first experimental phase focused on assessing the effect of coil diameter on sensor response, under varying acoustic frequencies at two discrete sound pressure levels.

In a subsequent stage, the spatial configuration of the acoustic source relative to the sensor was systematically varied to evaluate directional sensitivity. The speaker was initially placed adjacent to the diaphragm and posteriorly moved to distances of 2 cm, 3 cm, and 4 cm along the fiber axis. Then, at a fixed distance, the speaker was rotated 30° from the central axis to introduce angular displacement.

For each combination of frequency, volume, distance, coil diameter, and angular position, the

measurements presented in this paper represent the average result of ten repeated tests, ensuring statistical consistency and reliability.

When the acoustic vibration reaches the membrane, it is transmitted to the fiber, causing deformation in the coils. These deformations manifest as variations in voltage, which are observed by the oscilloscope. Subsequently, the time-domain signal displayed on the oscilloscope was converted into a frequency spectrum using the Fast Fourier Transform (FFT), allowing the observation of the predominant frequency of the sound wave produced by the speaker. This approach provided a characterization of how periodic variations in coil radius, induced by acoustic stimuli of different frequencies, affect the optical attenuation and spectral sensitivity of the sensing system.

Results and Discussion

The signal evaluated in the experiment was detected through the deformation of the optical fiber geometry, which induced macrobending effects. A similar result was reported by Wang and colleagues [10], who demonstrated that external vibrations could lead to variations in the macrobending loss, resulting in measurable changes in the transmitted signal.

In the initial phase of the experiment, the influence of fiber coil diameter on optical attenuation under acoustic excitation was systematically investigated using three configurations: 25 mm, 20 mm, and 15 mm. Each setup was subjected to sinusoidal excitation at 200 Hz, 440 Hz, and 550 Hz, under two distinct sound pressure levels, corresponding to 100% and 50% of the speaker's output volume, as illustrated in Figures 3, 4, and 5.

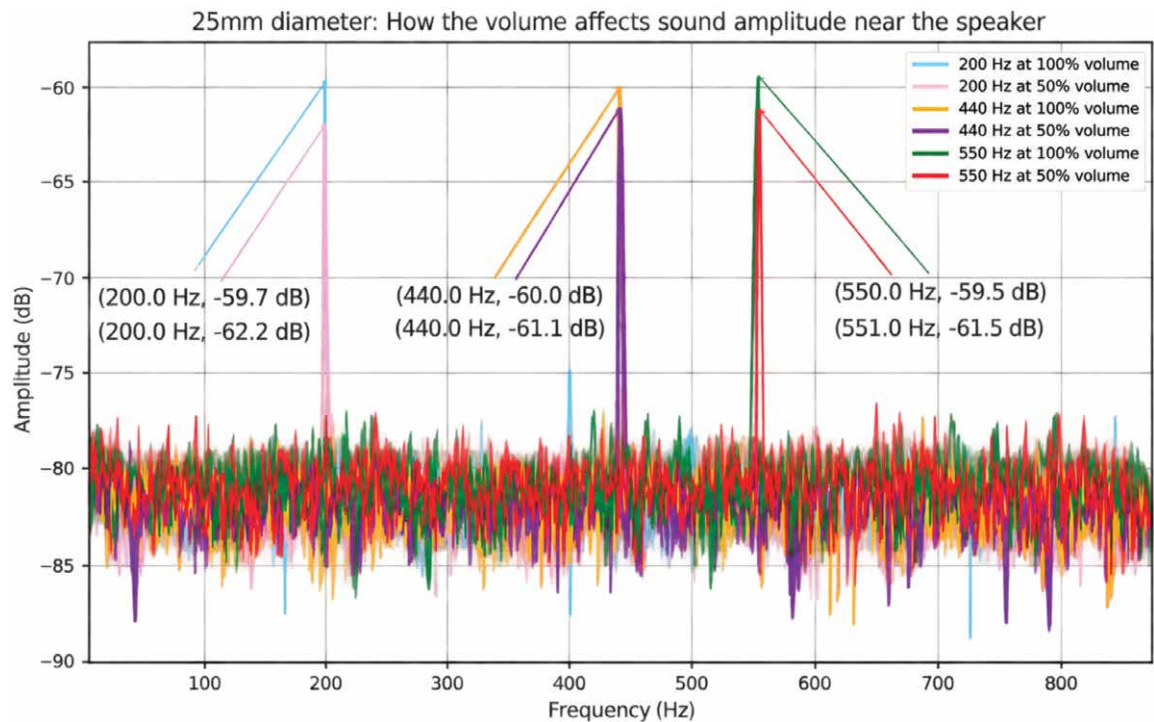
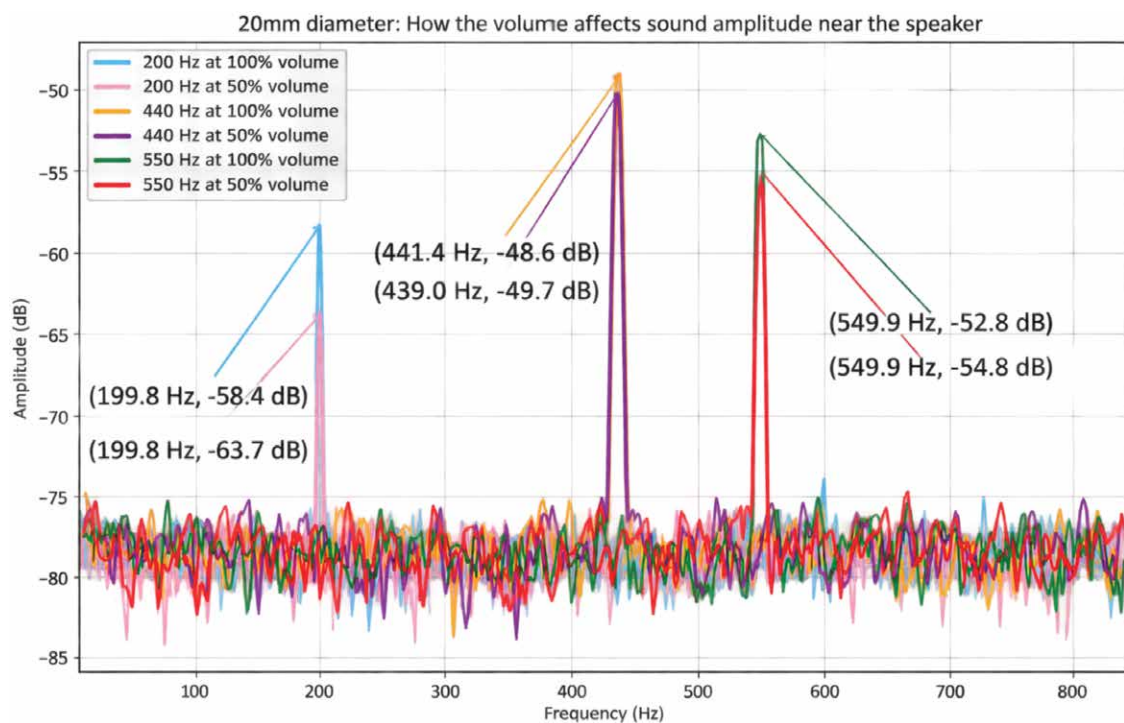
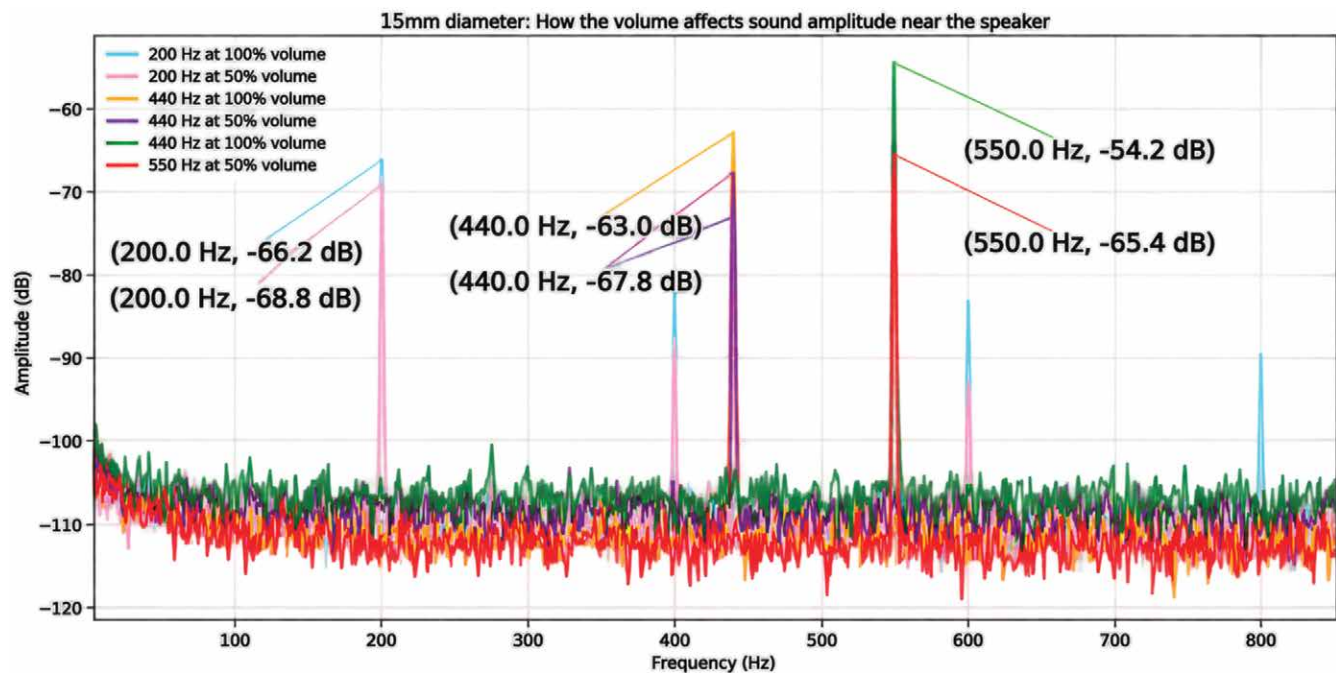
Figure 3. FFT of a 25 mm fiber coil under varying acoustic excitation levels.**Figure 4.** FFT of a 20 mm fiber coil under varying acoustic excitation levels.

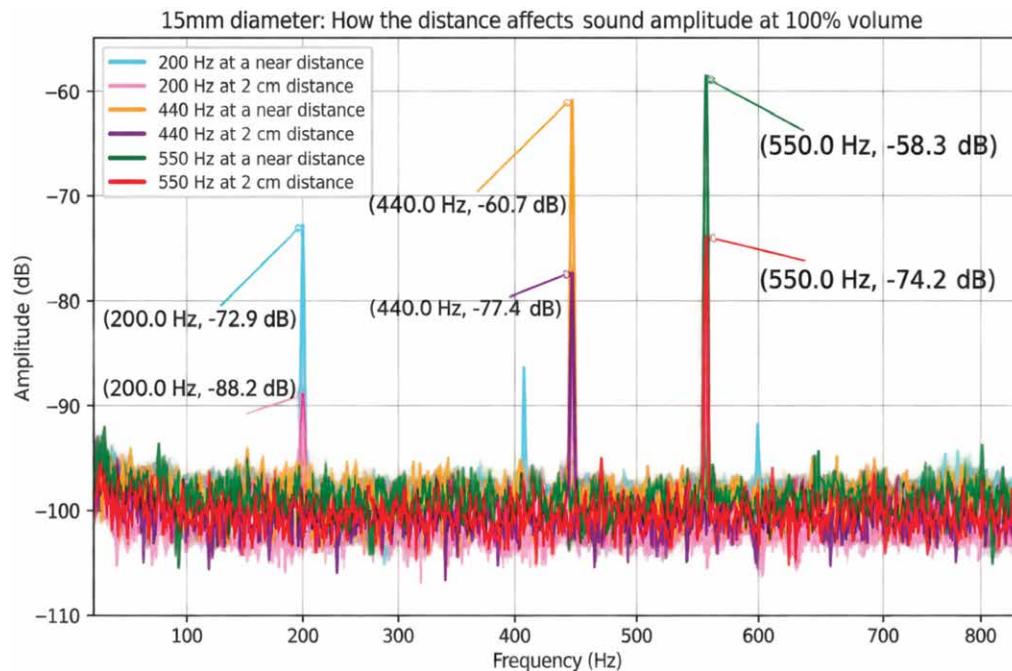
Figure 5. FFT of a 15 mm fiber coil under varying acoustic excitation levels.

The results reveal a pronounced dependence of the optical attenuation on the coil diameter. Among the tested configurations, the 15 mm coil exhibited the highest attenuation across all frequencies. This behavior confirms that tighter curvatures enhance macrobending-induced losses, thereby increasing the sensitivity of the system to acoustic perturbations. The attenuation between the two sound pressure levels causes a significant change in the amount of light that is lost along the optical fiber, that is, the sensor responds sensitively to changes in sound, strongly modulating the transmitted optical intensity. The 25 mm coil exhibited more stable attenuation values with smaller amplitudes across all frequencies, indicating lower sensitivity to acoustic excitation. This relative insensitivity is consistent with the weaker perturbation of the guided mode expected at larger bending radius.

Since the system with the 15 mm coil diameter demonstrated higher sensitivity and was more responsive to changes, the subsequent results presented in this paper focus exclusively on this diameter, although the same tests were conducted for all coil sizes.

In the second experimental phase, the effect of the relative positioning between the acoustic source and the fiber coil was examined. This analysis was conducted using the configuration that exhibited the highest sensitivity in the initial tests, a 15 mm diameter coil operating under 100% excitation volume. Two key parameters were systematically varied: the linear distance between the sound source and the fiber coil and the angular orientation of the acoustic source relative to the plane of the coil.

Figure 6 presents the optical attenuation data acquired with the acoustic source displaced by 2 cm from the coil, for three different frequencies. The results reveal a pronounced spatial dependence in acoustic sensitivity. In the sensing head employed in this study, the fiber does not interact directly with the acoustic field. Instead, the vibrating membrane acts as a transducer, converting acoustic pressure fluctuations into mechanical displacements that are coupled to the coiled fiber. As the source moves farther from the sensor, the sound intensity decreases, but the incident pressure field becomes more distributed due to diffraction and scattering in air, stimulating a broader region

Figure 6. FFT of a 15 mm fiber coil under varying acoustic excitation distance.

of the membrane. Therefore, the amplitude of the membrane's displacement is directly influenced by the incident sound pressure amplitude, which in turn is related to the square root of the sound intensity. This relationship is supported by classical acoustic theory [11] and confirmed in recent optical acoustic sensor models [6]. This behavior is further illustrated in Figure 7, which details the attenuation values for the 550 Hz excitation at increasing source distances. A similar result was discussed by Zhao and colleagues [12], where it was shown that the pressure of acoustic waves decays exponentially as they propagate along the pipeline, an attenuation behavior comparable to the inverse square law considered in this work.

To assess directional sensitivity, the source was rotated 30° relative to the coil axis while maintaining its proximity and excitation level. Figure 8 shows the attenuation of all three frequencies. Angular displacement resulted in a substantial increase in attenuation, especially at higher frequencies. This may be attributed to the modification of the incident acoustic wavefront on the membrane surface, which alters the spatial distribution of induced vibrations.

Figure 9 presents the results obtained from simultaneous excitation of two acoustic frequencies: 320 Hz and 325 Hz. The sensing system demonstrated the ability to resolve both frequency components independently. As in previous experiments, variations in sound pressure level, source distance, and angular orientation produced consistent effects on signal amplitude. A slight reduction in amplitude was observed when the volume was lowered, whereas increasing the distance between the sensing head and the speaker resulted in a more pronounced decline in signal strength, indicating once again the system's strong spatial dependence.

Conclusion

This study provides a comprehensive demonstration of the viability and effectiveness of a compact fiber optic sensing architecture, based on macrobending loss, for the detection of acoustic phenomena. The experiments established that the diameter of the fiber coil plays a pivotal role in determining sensor sensitivity, with smaller radii yielding greater attenuation in response to

Figure 7. FFT of fiber coil under different distances from acoustic excitation at 550 Hz.

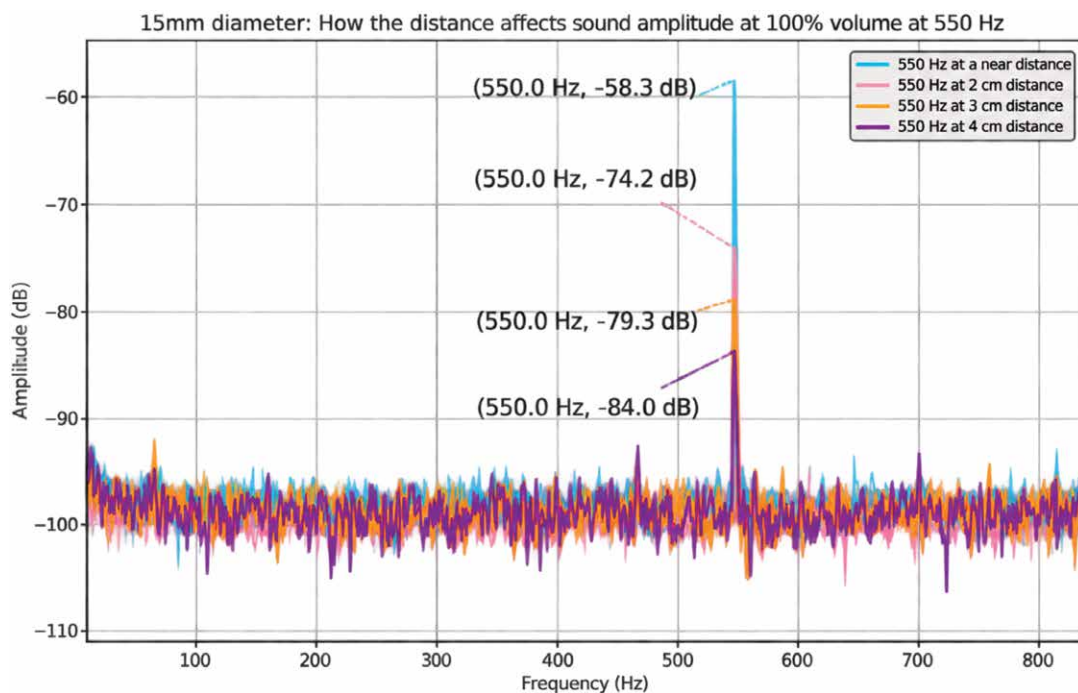
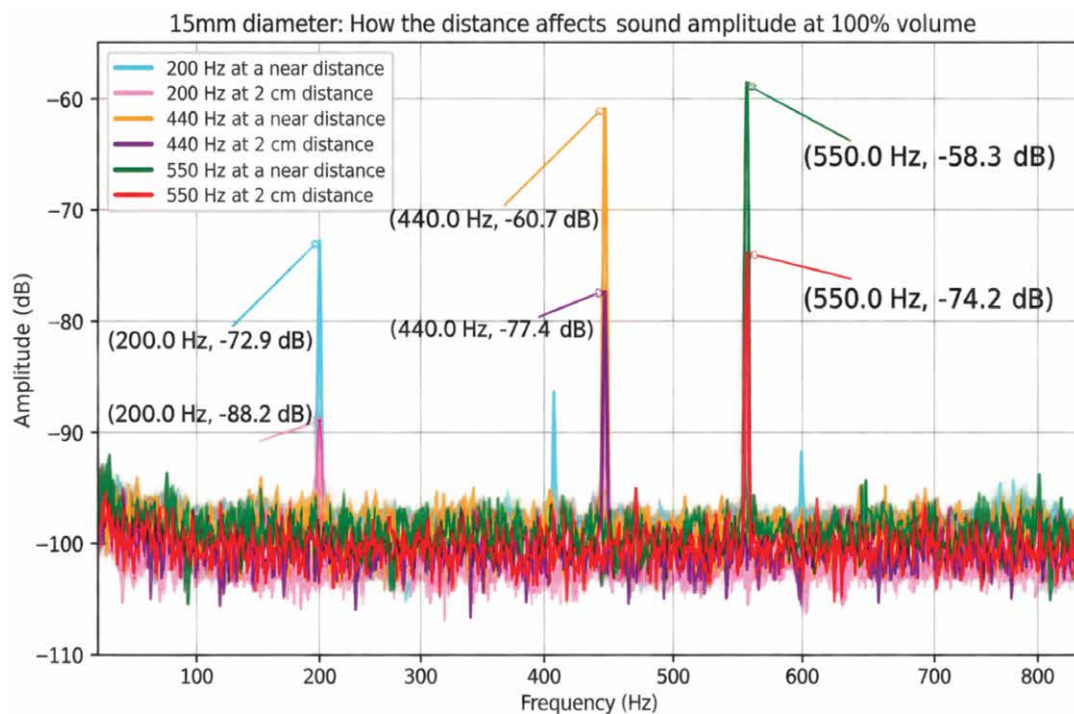
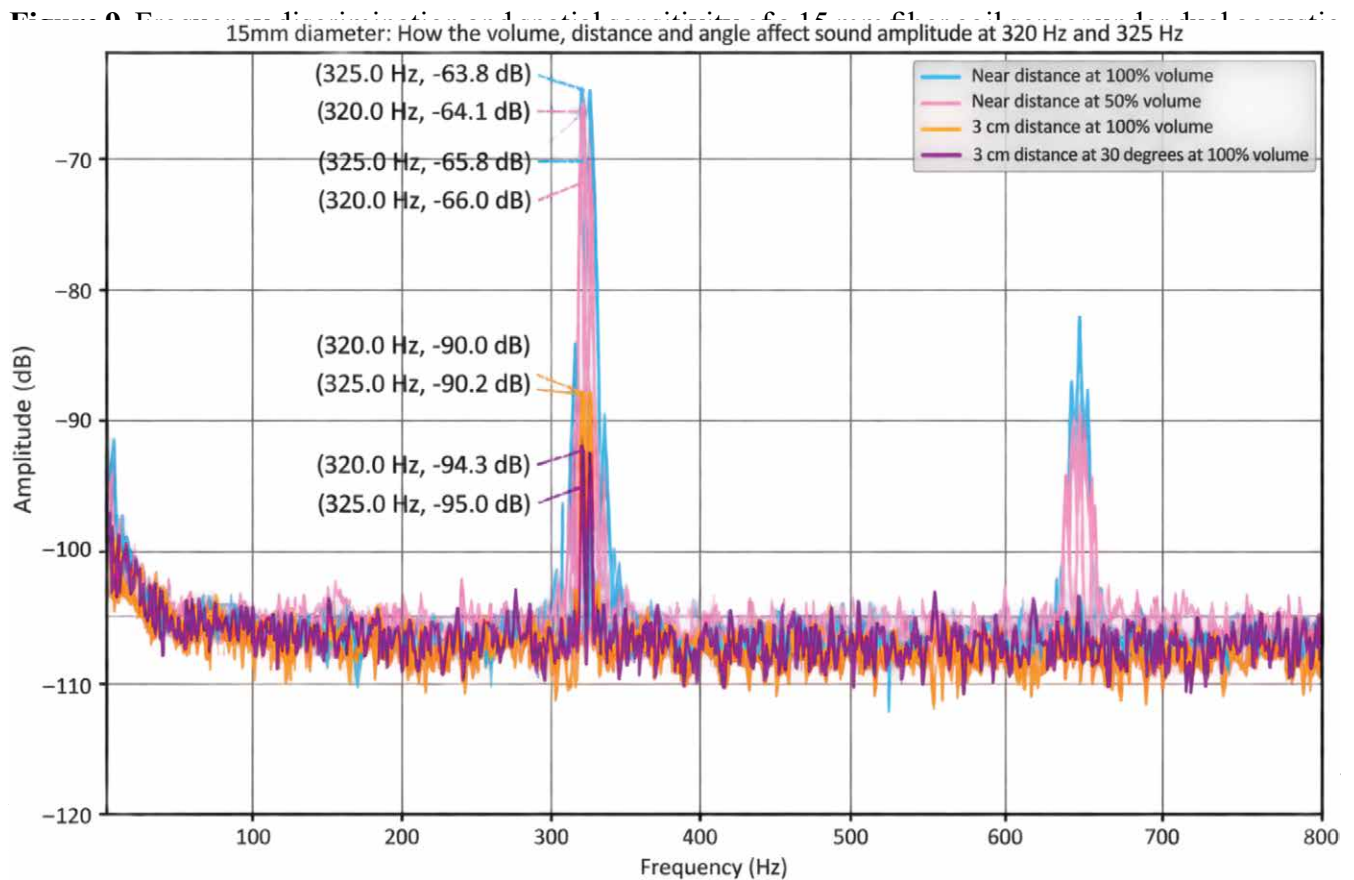


Figure 8. FFT of a 15 mm fiber coil under varying angular displacement.





The influence of spatial parameters such as source distance and angular incidence was investigated. The optical response exhibited a nonlinear dependence on distance, while also displaying directional sensitivity under oblique wave incidence.

Notably, the sensor demonstrated the ability to resolve two simultaneous acoustic frequencies (320 Hz and 325 Hz), despite their narrow separation, underscoring its high spectral resolution and selectivity.

As demonstrated in this study, the proposed system offers operational advantages, recognizing variations in frequencies, sound pressure levels, distances, and angles. These findings position membrane-coupled fiber sensors as a cost-effective and scalable solution for acoustic monitoring applications. Moreover, they provide immediate detection without the risk of explosions or fires, which is highly beneficial in leak scenarios.

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Model for Pre-Design of Darrieus wind Turbine H-Type

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This work presents a simplified fluid-structure interaction model for pre-design of a Darrieus wind turbine. The modeling of Darrieus turbine is a challenging task due to the aerodynamic complexity associated with its operation. One challenge is determining the drag and lift coefficients for each position during the circular motion of the blades, due mainly to changes in Reynolds number and angle of attack. Structural calculations are also challenging, as the blades operate in a rotating bending regime and must withstand alternating loads. For the development of the mathematical model of this work, the main geometric and operating parameters of the turbine were considered, and can be used to estimate aerodynamic forces, torque, and blade structural deflections. To characterize the profile's aerodynamic behavior, lift and drag coefficient data obtained from the airfoil-tools website, based on data from the XFOIL software, were used. The mathematical model was implemented in a Scilab code, allowing simulation of the turbine operation under different conditions. The graphs presented were generated by the developed code. It was considered that the turbine operates at constant rotational velocity. The radial and tangential forces on the blades were determined from the lift and drag components, as a function of the instantaneous angle of attack. Subsequently, the torque was calculated during the movement, allowing estimation of the available power. The blade deflections were analyzed, considering the distributed loads and the cross-sectional moment of inertia, based on a simplified modeling of a bi-supported beam. The results obtained allow a preliminary assessment of the turbine aerodynamic performance and structural integrity. The model can provide initial design support, with low computational cost and good applicability in conceptual stages.

Keywords: Darrieus Turbine. Pre-Design. FSI. Fluid-Structure Interaction. Aerodynamics Simulation. Structural Simulation.

Wind turbines convert wind kinetic energy into electrical energy, playing an increasingly central role in the global energy mix as renewable and sustainable sources. Wind turbines can generally be divided into two categories: horizontal-axis wind turbines (HAWT) and vertical-axis wind turbines (VAWT) (Figure 1) [1].

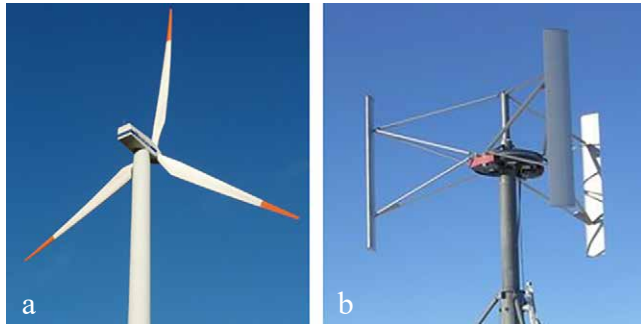
HAWTs are the most common, with large blades rotating around an axis parallel to the ground, while VAWTs operate with blades rotating around an axis perpendicular to the ground, allowing wind to be captured from any direction. In particular, the Darrieus turbine (DT) consists of airfoils rotating around a central axis (Figure 1b). In these models, the blades can be straight, as is the case

with the H-type. DT operates by generating torque from aerodynamic lift. Its design makes it suitable for urban or building-integrated applications due to its lower sensitivity to wind direction. However, one of its typical limitations is difficulty in self-starting, which can be overcome through optimized geometries or starting systems [2].

The pre-design of DT is a challenging task due to the aerodynamic complexity associated with its operation. One challenge is calculating the drag and lift forces during the circular motion of the blades, due to changes in Reynolds number, angle of attack, and the nonlinear effects of aerodynamic stall (boundary layer detachment) and wake formation. Structural calculations are also challenging, as the blades operate in a rotating bending regime and must withstand alternating loads. Another challenge is determining the tip speed ratio, which directly influences turbine efficiency but depends on wind velocity and the chosen blade aerodynamic profile. Finally, the

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Figure 1. (a) HAWT e (b) VHTT.

development of detailed DT designs requires iterative numerical methods, or numerical simulations based on volumes or finite elements, to couple aerodynamic and structural dynamics models [3].

Several studies in the literature investigate the performance of Darrieus wind turbines, most of which are based on numerical simulations, with emphasis on the use of Computational Fluid Dynamics (CFD) simulations. Hosseini [1] proposed a hybrid turbine design, combining Bach-type Savonius rotors (another type of VAWT) with an H-type Darrieus rotor, to improve starting capacity and expand the operating range. Using CFD, the author identified that, although the isolated Darrieus rotor has a high power coefficient, its starting is limited. The hybrid configuration improved the overall system efficiency and performance, even at low wind speeds.

Rogowski [2] investigated the aerodynamic performance of H-type DTs with different profiles from the NACA series. Using CFD, the author concluded that the NACA 1418 profile offers the best performance in blade configurations, achieving an optimal power coefficient, and is a promising option for future vertical turbine designs. Siregar [3] presented two relevant studies. The first is a comprehensive literature review on H-type Darrieus rotors, covering topics such as aerodynamic modeling, CFD simulation techniques, starting behavior, blade-vortex interaction, and design optimization strategies. The second paper describes the development and simulation of a DT optimized for operation in

low-wind-speed regions. The proposed model's performance was evaluated through CFD, demonstrating its viability for small-scale power generation.

Singh [4] and Ghiasi [5] investigated the impact of geometry on H-type DT performance. Ghiasi identified an ideal height-to-diameter ratio to optimize aerodynamic efficiency at low tip speeds, while Singh, through 3D simulations, showed that lower aspect ratios favor performance in exhaust flows, highlighting the influence of geometry on turbine adaptation to operating conditions. These works show the importance of numerical simulations as essential tools for the study and development of DT; however, there is little development of models for pre-dimensioning, which makes this a motivator for the development of the present work.

Objective

The objective of this work is to present a proposed model for the pre-design of a Darrieus wind turbine H-Type. The preliminary dimensioning consists of developing an initial geometric model so that more accurate numerical simulations can be performed during turbine design development.

The methodology proposed in this work applies basic principles of aerodynamics and material strength to develop a simplified mathematical model of fluid-structure interaction (FSI). The turbine will be assumed to be operating at constant velocity. This calculation will require determining the forces and moments on the blades, and the results will be used to calculate stress and blade deflection. In this proposal, the determination of aerodynamic forces (drag and lift) will be performed using data from the airfoiltools website, which mainly uses results from the XFOIL (free software used to calculate aerodynamic forces on airfoils in subsonic flow). The software combines potential flow theory with approximate solutions for fluid-dynamic boundary-layer flow and is widely used in aeronautical engineering and wind

turbine design, for example. However, XFOIL is limited to two-dimensional geometries and does not capture the nonlinear effects of flow, which can be solved with the Navier-Stokes equations in finite volume software, for example. On the other hand, deflection and stress distribution calculations are performed using classical beam element theory.

Mathematical Model

In general, wind turbines can be characterized by two parameters: the blade tip speed ratio (λ) and the power coefficient (C_p). The first parameter relates the turbine rotational velocity to the wind velocity, such as:

$$\lambda = \frac{R\omega}{U} \quad (1)$$

where R is the radius of the turbine rotor, ω is the angular velocity of the blades, and U is the wind velocity. The second parameter relates the power available in the wind to the mechanical power developed by the turbine: (2)

$$C_p = \frac{T\omega}{0,5\rho AU^3} \quad (2)$$

where T is the torque generated by the turbine, ρ is the specific mass of the fluid (in this case, air), and $A = 2Rb$ is the effective wind capture area. Graphic 1 illustrates the variation of C_p with λ for some types of wind turbines, and Figure 2 illustrates the DT model considered in this work

In DT, the local Reynolds number and angle of attack change according to the circular motion of the blades. The blade experiences an incident flow with the magnitude and direction of the relative velocity (relative flow), and therefore, the aerodynamic data are determined based on this velocity. Figure 3 shows the aerodynamic forces acting on the blade. The drag force is parallel to the relative flow direction, and the lift force is perpendicular to the relative flow direction. It is worth noting that, based on the results of the mathematical model for a single blade, it is possible to calculate the contribution of the other

Graphic 1. Power coefficient as a function of tip speed ratio for 3 types of wind turbines.

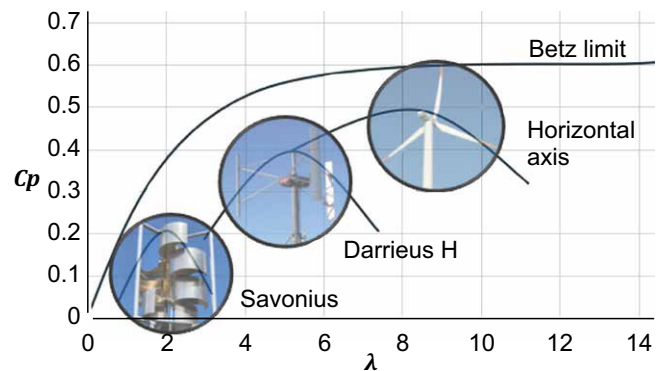


Figure 2. H Darrieus wind turbine H-Type model.

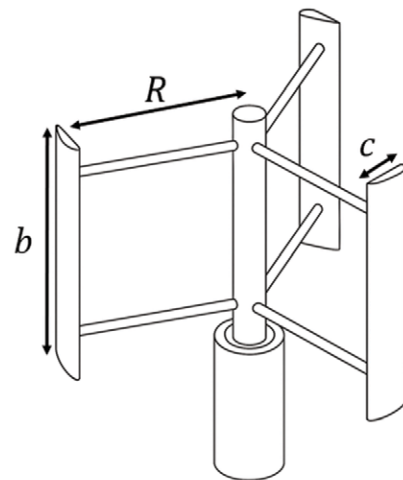
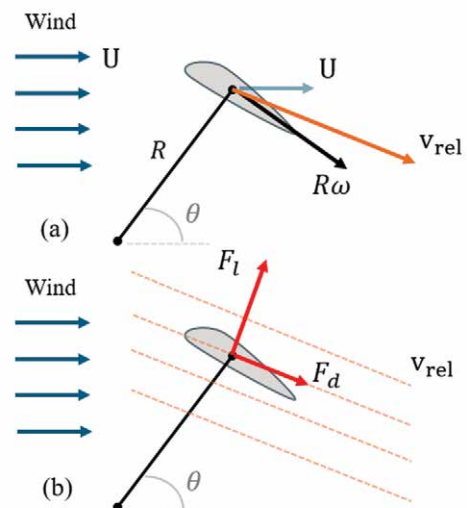


Figure 3. (a) Velocity decomposition on Darrieus turbine blade, and (b) drag and lift forces on blade.



blades to the forces and moments on the turbine. Based on Figure 3, the relative velocity can be calculated as:

$$v_{rel} = U\sqrt{(\lambda + \sin\theta)^2 + (\cos\theta)^2} \quad (3)$$

where θ is the angular displacement of the blades (blade position), which is the independent variable that varies from 0 to 2π with each blade revolution. Thus, the local Reynolds number can be calculated as:

$$\mathcal{R} = \frac{\rho c v_{rel}}{\mu} \quad (4)$$

where c is the airfoil chord, and μ is the dynamic viscosity of the air. The angle of attack is formed by the reference line of the airfoil chord with the direction of the relative flow, that is:

$$\alpha = \text{atan}\left(\frac{\cos\theta}{\lambda + \sin\theta}\right) \quad (5)$$

With the Reynolds number and angle of attack calculated for each turbine position θ , it is possible to determine the coefficients and calculate the aerodynamic forces as:

$$F_{d,l} = 0,5\rho v_{rel}^2 bc C_{d,l} \quad (6)$$

where the drag and lift coefficients are $C_d(\mathcal{R}, \alpha)$ and $C_l(\mathcal{R}, \alpha)$, respectively. In this work, these coefficients are determined using data from airfoiltools.

In DT, the tangential force distribution (7) produces the torque required to calculate the power coefficient, while the radial force distribution (8) is used for the structural calculation.

$$F_t = F_l \sin \alpha - F_d \cos \alpha \quad (7)$$

$$F_R = F_l \cos \alpha + F_d \sin \alpha + m R \omega^2 \quad (8)$$

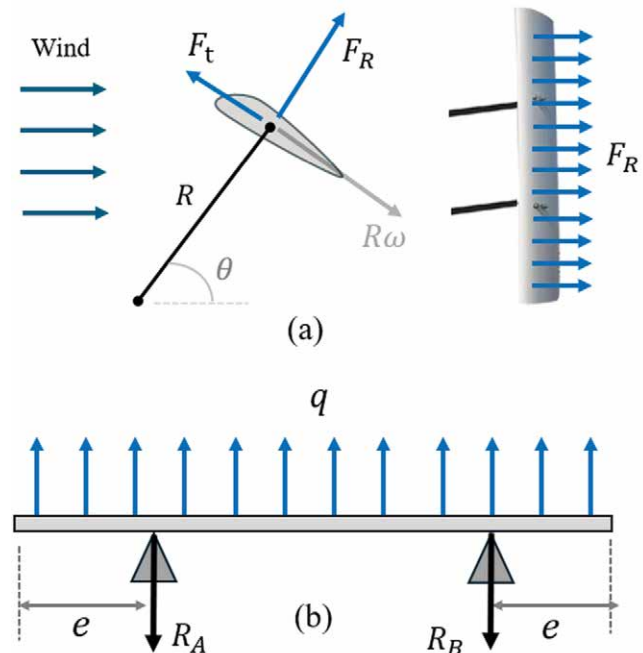
where $m R \omega^2$ is the centrifugal force due to blade rotation, m is the blade mass, and R is the rotor radius. To calculate the total force generating the torque on the turbine, it is necessary to consider the contribution of the other blades. Thus, for three blades the phase shift angle is 120° , so:

$$F_{tot} = F_t|_{\theta} + F_t|_{\theta+120} + F_t|_{\theta+240} \quad (9)$$

The torque acting on the turbine shaft is $T = F_{tot} R$, the power is $P = T\omega$, and the power coefficient calculated by equation 2.

With the forces determined, a blade free-body diagram can be developed for structural calculation. It was assumed that the forces are distributed uniformly along the length of the blade in a bi-supported beam model, as illustrated in Figure 4. The beam will be subjected mainly to radial loads. With $q = F_R/b$ defined, it is possible to calculate that the reactions at the supports are $RA = RB = 0.5qb$. Thus, the solutions for the bending moment and deflection can be determined according to equations 10 and 11, respectively, for any position x along the length of the blade, starting from one end of the blade.

Figure 4. (a) Free-body diagram of the blade, and (b) bi-supported beam model.



$$M(x) = 0,5qx^2 - R_A\langle x - e \rangle^1 - R_B\langle x - (b - e) \rangle^1 \quad (10)$$

$$v(x) = \frac{1}{EI} \left[\frac{qx^4}{24} - \frac{R_A\langle x - e \rangle^3}{6} - \frac{R_B\langle x - (b - e) \rangle^3}{6} + C_1x + C_2 \right] \quad (11)$$

where e is the distance from the blade ends to the support, E is the linear elasticity modulus of the blade material, and I is the moment of inertia of the blade cross-section, which will depend on the geometry of the chosen airfoil. The constants C_1 and C_2 can be calculated by solving the linear system resulting from the conditions $v = 0$ at $x = e$ and $x = b - e$, so that:

$$\begin{bmatrix} e & 1 \\ b - e & 1 \end{bmatrix} \begin{Bmatrix} C_1 \\ C_2 \end{Bmatrix} = \begin{Bmatrix} -qe^4/24 \\ -q(b - e)^4/24 + R_A(b - 2e)^3/6 \end{Bmatrix} \quad (12)$$

Finally, the stress distribution due to bending moment can be calculated as:

$$\sigma = My/I \quad (13)$$

where y corresponds to half the maximum airfoil thickness.

Numerical Implementation

The mathematical model was implemented in Scilab code. The main input parameters are the rotor radius (R), blade height (b), airfoil chord (c), distance from the blade ends to the supports (e), wind velocity (U), blade tip speed ratio (λ), and blade mass (m). Thus, the rotation of the turbine can be calculated using equation (1). In the sequence, the angle θ was implemented, varying from 0 to 2π , divided into n_p points, and the relative velocity, the Reynolds number, and angle of attack were calculated.

The aerodynamic coefficient data were determined using a linear interpolation algorithm (based on data from airfoiltools). The data were organized into tables for a range of Reynolds numbers, with a relationship between the variables: angle of attack, lift coefficient, and drag for each Reynolds number. The algorithm identifies the Reynolds number calculated for a position θ , interpolates the variables from the table, and then, when it identifies the angle of attack (at θ), stores the lift and drag coefficient values at that position. Thus, the aerodynamic forces are calculated using

equation (6), the tangential (7) and radial (8) components, the total force (9), and finally the torque and power coefficient (2).

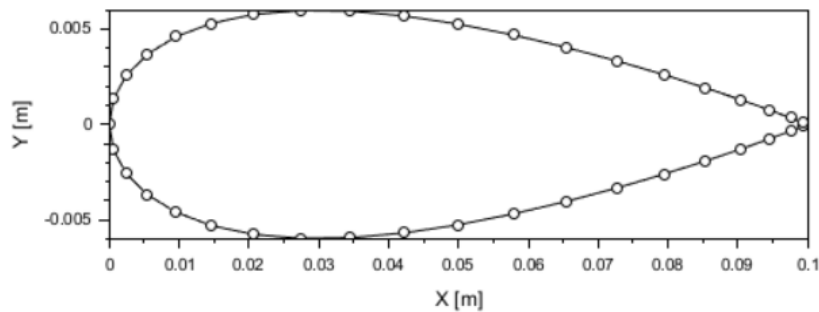
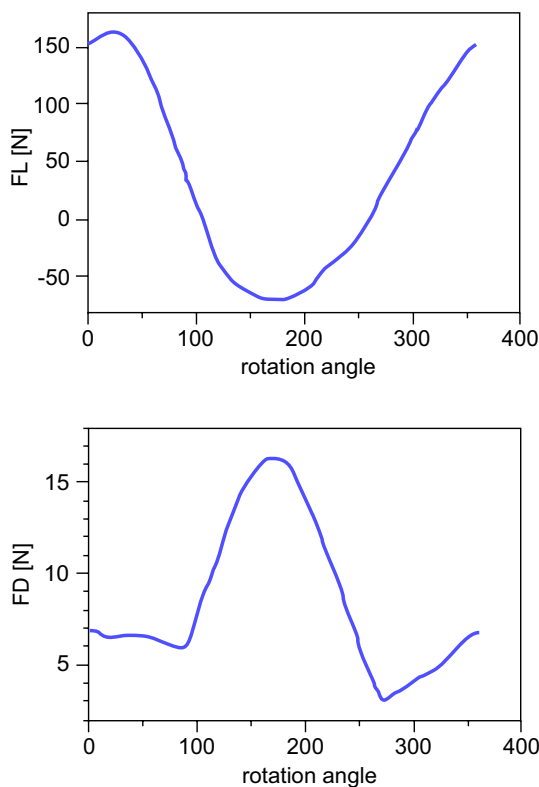
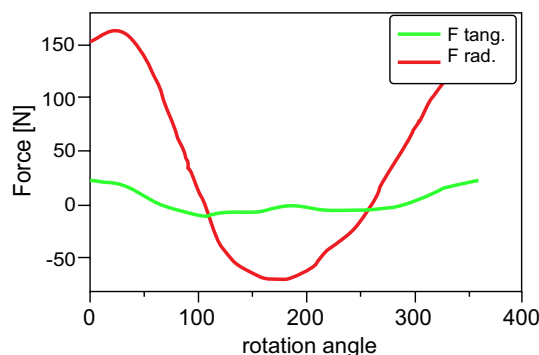
For the structural calculation, the distributed force q was calculated, and equations (10) to (13) were used to determine the stress and deflection distribution along the blade.

Results

The results presented consist mainly of graphs of aerodynamic forces for each θ position, the tangential and radial forces, the torque generated by the turbine, the maximum stress for each θ position, and a graphical representation of the turbine and a blade deflected at the position where the stress is maximum. Only one design case was evaluated, with the input parameters described in Table 1. The value of $\lambda = 5$ was defined as shown in Graphic 1, considering the maximum value of C_p . The variable θ (0 to 2π) was divided into $n_p = 60$ points. For the blade profile, the symmetrical airfoil NACA0012 was considered due to its wide use for academic studies (Graphic 2).

When calculating the Reynolds number, it is important to verify that the range of values is consistent with the airfoiltools data. In this case, the data corresponds to the range of 100,000 to 1,000,000, and the calculated values correspond to 198,000 to 297,000. The interpolated lift and drag values, as a function of position θ (in degrees), are presented in Graphic 3. Graphic 4 shows the distribution of tangential and radial forces as a function of position θ . Note that radial forces predominate. Therefore, in this work, only radial forces were considered for structural calculation. Additionally, the moment of inertia is greater in the direction of the moment caused by tangential loading.

Graphic 5 shows the torque in the turbine considering one and three blades. Note that one blade is not sufficient to maintain the torque in a single direction, contrary to the use of three blades, which maintain positive torque. Graphic 6 shows the maximum stress during the movement, acting

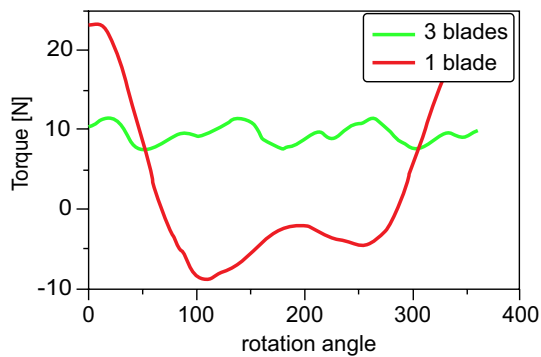
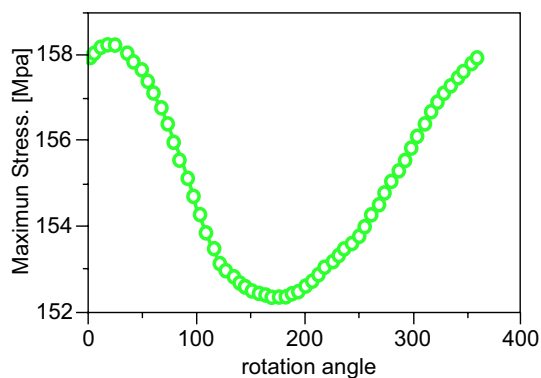
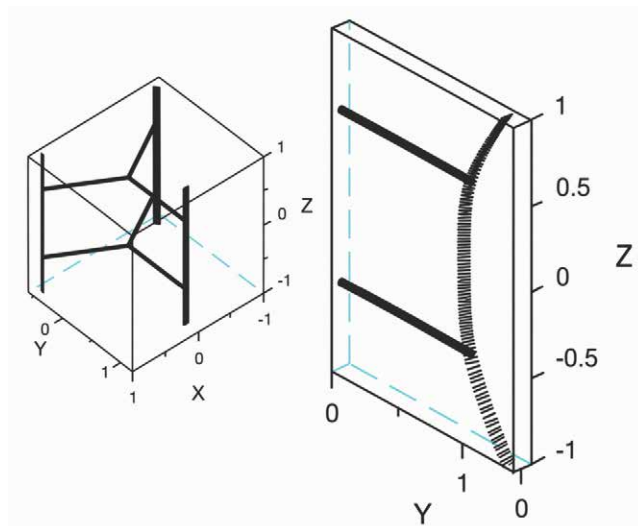
Graphic 2. NACA0012 airfoil.**Graphic 3.** Lift and drag forces on blade.**Graphic 4.** Tangential and radial forces.

on the rod attachment points (as can be verified by the bending moment diagram of a bi-supported beam). Graphic 7 shows the representations of the turbine, and a blade deflected at the maximum stress position, near the start of the movement (on a scale increased 10 times). Finally, Table 2 presents the results for some turbine operating parameters for the provided input data in Table 1. Note that the power coefficient (0.43) was higher than the reference in Graphic 1 for $\lambda = 5$ (0.40), but this is justifiable because mechanical and generator losses were not considered.

Conclusion

This work presented a simple fluid-structure interaction model for pre-design of Darrieus wind turbine H-Type. The aerodynamic coefficients were determined through a linear interpolation algorithm based on data from the airfoils tools website. Tangential and radial forces, moments, stress distributions, and deflection were then calculated. In general, the lift force was higher than the drag force, indicating that the input parameters and chosen aerodynamic profile were appropriate. The torque generated by the turbine (3 blades) shows that the direction of rotation is constant during movement. Finally, stress and deflection distributions allow assessment of whether the pre-design meets engineering criteria.

It is important that future studies be conducted to validate the proposed model, either through more precise numerical methods or experimental data.

Graphic 5. Tangential and radial forces.**Graphic 6.** Maximum stress on external blade surface.**Graphic 7.** Maximum deflection.

Acknowledgement

We thank Senai Cimatec University for the support and resources allocated to the development of this work.

Table 1. Input parameters.

Rotor Radius (R)	1,0 m
Blade Height (b)	2,0 m
Airfoil Chord (c)	0,1 m
Support Distance (e)	0,5 m
Wind velocity (U)	7 m/s (25,2 km/h)
Air density (ρ)	1,2 kg/m ³
Air dynamic viscosity (μ)	1,8 kg/ ms
Elasticity modulus (blade) (E)	70 GPa
Blade mass (m)	5 kg
Moment of inertia (I)	1,4 10^{-8} m ⁴

Table 2. Calculated operating parameters.

Rotation	334,22 RPM
Average turbine torque	10.60 Nm
Average turbine power	334 W
Average turbine power coef.	0,43

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Pathways for Dispensing Upper Limb Prostheses in Bahia - Brazil

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Access to prostheses for amputees presents problems in terms of dispensing efficiency, whether due to budgetary issues or the lack of expansion of health care centers for people with disabilities. The Specialized Rehabilitation Centers are outpatient rehabilitation centers that diagnose, treat, prescribe, adapt, and maintain assistive technologies, such as prostheses, and serve as a reference for the healthcare network in the territory. However, in the state of Bahia, the procedures for dispensing upper limb prostheses contrast with those for lower limb prostheses. This article presents an overview of prosthesis dispensation in Bahia, as well as the paths that amputees take to obtain an upper limb prosthesis, and shows through documentary research the incompleteness of actions closer to the municipalities where amputees live, in addition to the time it takes to access the prosthesis.

Keywords: Prosthesis Coverage and Dispensation. Upper Limb Prostheses. Territory and Health Residence.

The granting of Orthotics, Prostheses and Means of Locomotion (OPM) must respect the specific needs of each patient, allowing for the necessary adaptations and a systematic assessment and monitoring process. These concessions operate through the Care Network for People with Disabilities (RCPD), which is an initiative to care for people with disabilities, in their particularities and specificities, within the Unified Health System (SUS)[1,2].

The actions to expand the supply of prostheses and orthoses, as well as care for other disabilities, are integrated into the RCPD by the Specialized Rehabilitation Centres (CER), which are outpatient care centers specializing in rehabilitation that carry out diagnosis, treatment, granting, adaptation and maintenance of assistive technology, constituting a reference for the health care network in the territory, and which may have a fixed or itinerant Orthopaedic Workshop service.

In Brazil, 7,3% of the population aged two and over were people with disabilities, corresponding to 14,4 million Brazilians [3]. According to the IBGE

(2025), people with disabilities are those who have great difficulty or are unable to carry out day-to-day activities in any way in the functional domains of seeing, hearing, lower limbs, upper limbs and mental limitations, even when using AIDS [4].

In the upper limb domain, situations involving the use of the limb for strength and coordination activities in the arm or shoulder are linked with permanent difficulty in picking up small objects or opening and closing bottle tops, even when using prostheses and devices, this domain encompasses people with upper limb amputation.

Amputation procedures imply the need for prostheses so that amputees can try to resume their daily activities, albeit through rehabilitation processes. However, amputees face problems in accessing prostheses, and the difficulties in dispensing OPM are manifold, ranging from administrative and budgetary challenges to logistical and technological issues, and aspects related to human behavior [5].

All these problems directly affect disabled people's access to the materials dispensed, preventing them from maintaining their physical and mental health, social inclusion and quality of life. This article seeks to present the path to granting upper limb prostheses to amputees in the state of Bahia, Brazil, based on documentary research from sources such as regulatory documents and SUS databases.

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Amputations in Numbers

Amputation is the term used to define the total or partial removal of a limb, which is a treatment method for various diseases, usually complications of chronic degenerative diseases and traumatic causes such as traffic accidents and firearm injuries [6].

In Brazil, from 2008 to 2020, the DataSUS database documented 659,329 amputation procedures related to upper and lower limbs, including finger amputation or disarticulation [7]. However, from the perspective of categorising upper limb and lower limb amputation, the data on the procedure does not indicate whether the disarticulation or amputation is of fingers or toes. Consequently, with a view to ensuring adequate representation, data pertaining to cases of finger amputation or disarticulation will be excluded from the study. As demonstrated in Figure

1, the population with the highest rates of amputation is in the 50s. This finding is in line with the indices of the IBGE (2025), which show that 2,2% of the population aged 2 to 14 had some kind of disability. In the 15 to 59 age group, this percentage rises to 5,4%, and reaches 27,5% among people aged 70 or over.

In the state of Bahia, individuals living with disabilities constitute 7,9% of the total population, amounting to 1,1 million people. It is estimated that 1,4% of the population experiences issues related to the upper limb, including difficulty picking up small objects or opening and closing lids. This group includes individuals who have undergone upper limb amputation [4].

The number of upper limb amputations is related to wrist amputation or disarticulation, followed by upper limb amputation or disarticulation, which

Figure 1. Amputation procedures by type and age group: 2008-2020.

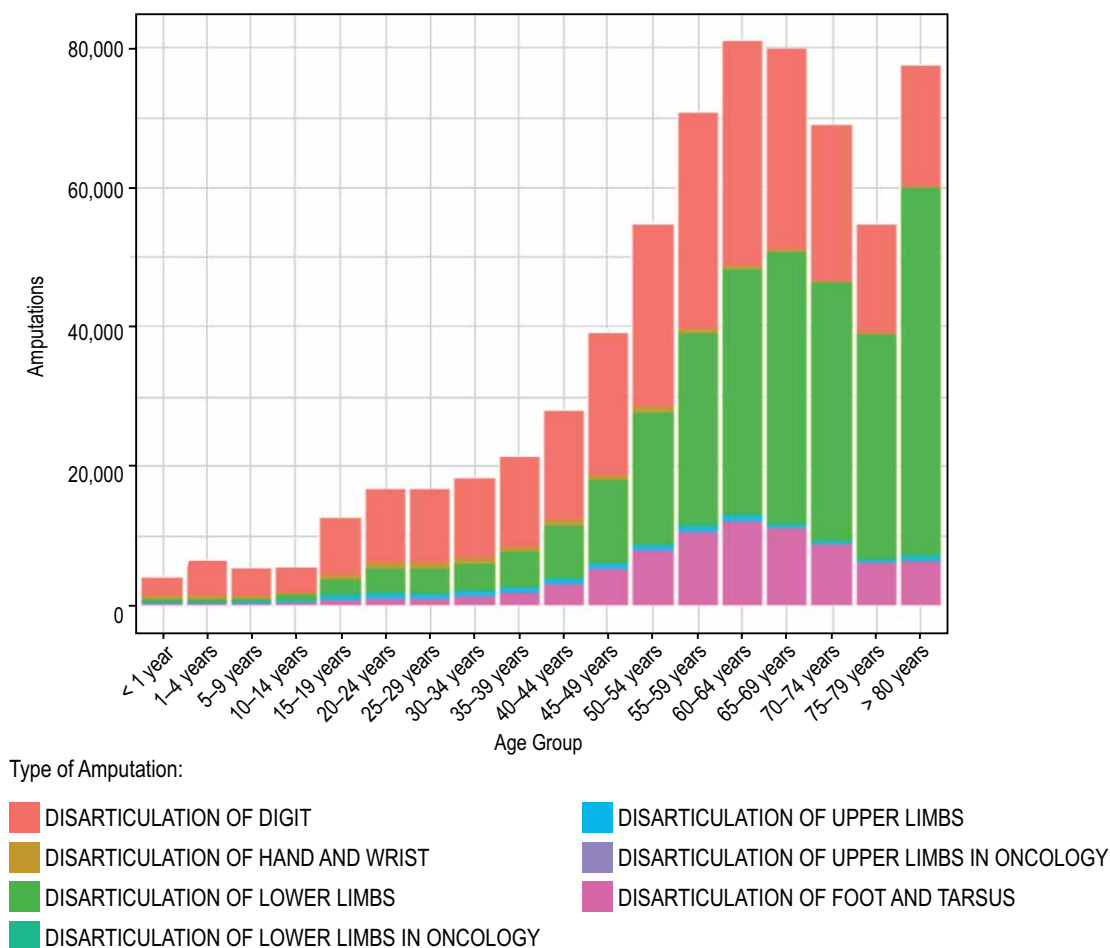
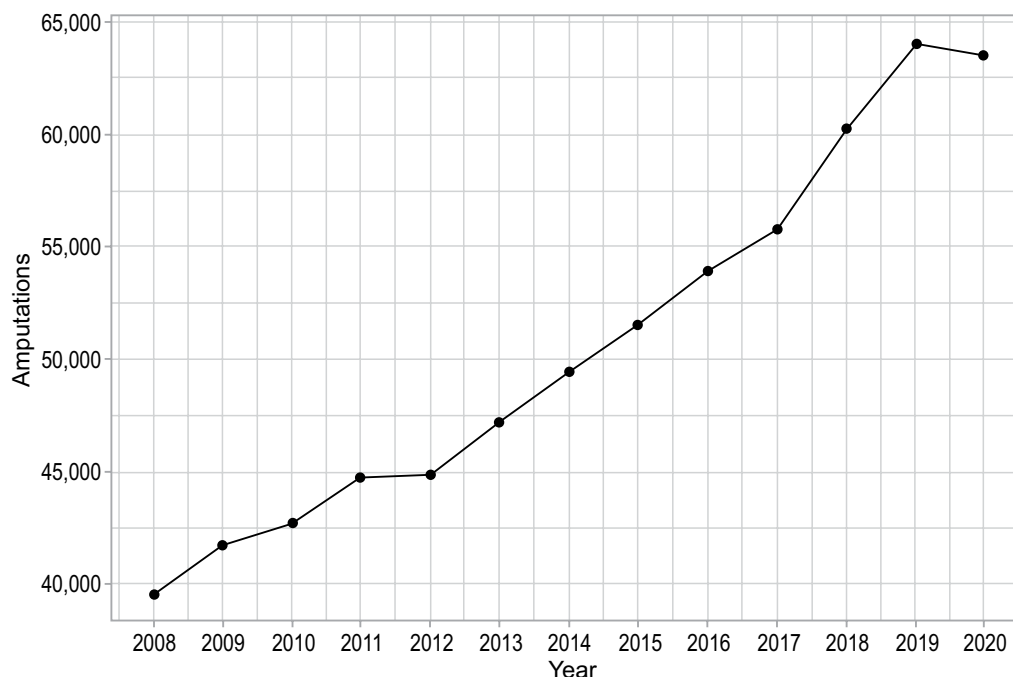


Figure 2. Amputation in Brazil, 2008-2020.

Source: Prepared by the author based on DATASUS/SIH/SUS, 2025.

does not accurately determine the level of the upper limb amputation procedure. The age groups with the highest number of amputations are 30 to 44 years old, as shown in Figure 3.

Although the number of municipalities for which patients are hospitalised for amputation procedures is poorly distributed within the same health macro-region, as shown in Figure 4, there are nine health macro-regions in Bahia. When looking at the municipalities of origin of patients who have undergone amputation, the distribution of amputation occurrences is wider, Figure 5. In both figures, the municipality of Salvador has the highest total due to its demographic density and the number of healthcare establishments in the capital of Bahia.

The Care Network for People with Disabilities in Bahia

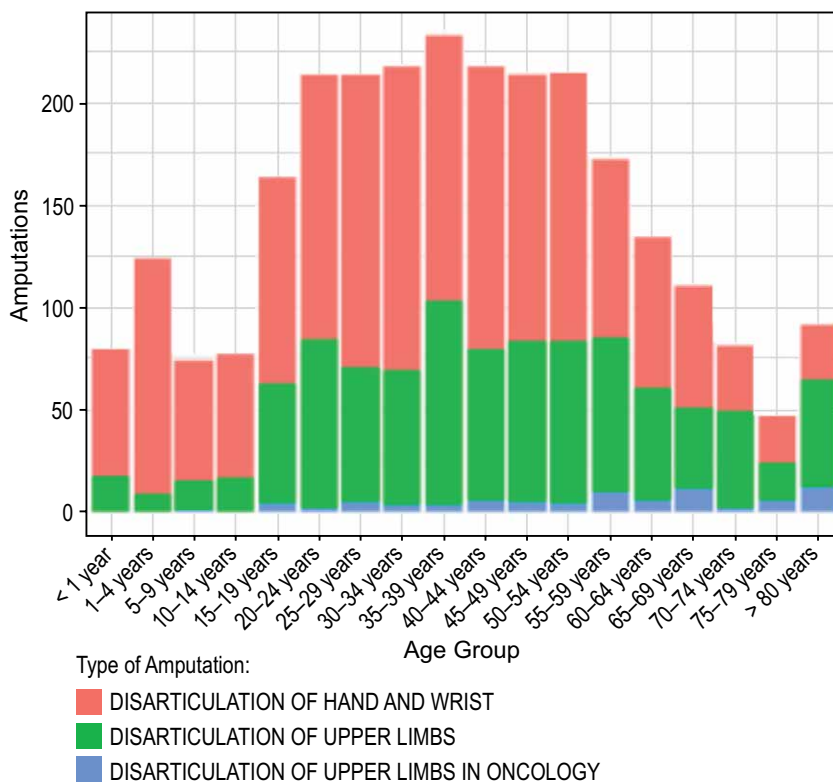
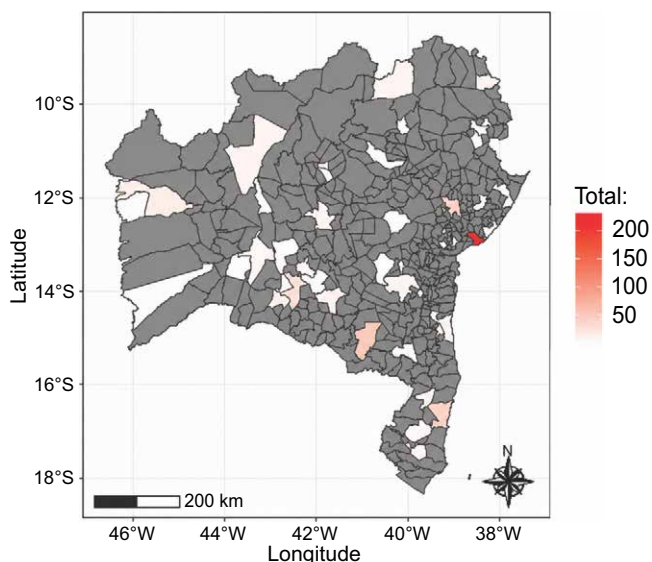
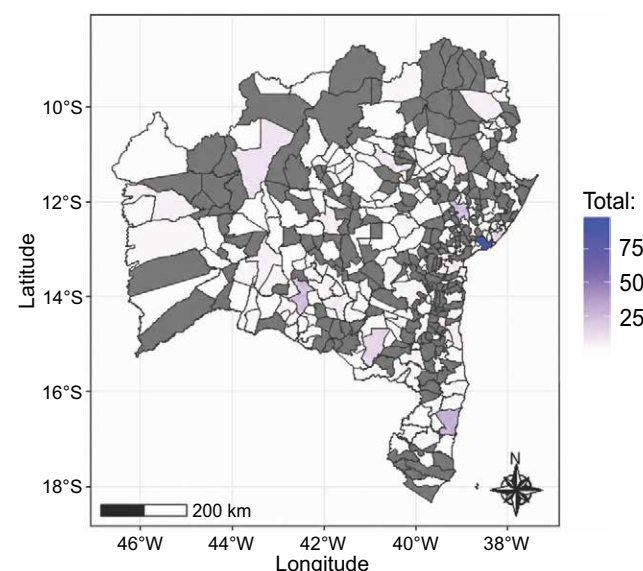
The number of amputation procedures has increased, Figure 2, implying an increase in demand for orthoses, prostheses and mobility aids (OPM) for this population. The RCPD seeks to expand and coordinate healthcare provision for

people with temporary or permanent disabilities, and one of its specific objectives is to increase the supply of OPM

The CER is an integral and essential part of the RCPD and can be organised according to the type of rehabilitation modality provided: hearing; physical; intellectual; and visual. They are classified as follows: CER II consists of two rehabilitation modalities; CER III consists of three; and CER IV consists of four. A CER qualified in physical rehabilitation must have the support of a fixed orthopaedic workshop.

The activities of the Orthopaedic Workshops aim to assist people with reduced mobility by creating, adapting and developing assistive technologies, as well as adapting and developing bespoke prostheses for amputees and people with congenital limb differences.

The prescription and dispensing of OPMs must be carried out by trained professionals and be subject to the completion and issuance of a justified report, in accordance with the rules established in the SUS regulations. Prior authorisation must also be obtained from the state or municipal manager,

Figure 3. Upper limb amputation procedures by type and age group in Bahia: 2008-2024.**Figure 4.** Upper limb amputations in Bahia by municipality of hospitalization: 2008-2024:**Figure 5.** Upper limb amputations in Bahia by municipality of residence: 2008-2024:

who must consider the justification presented in the prescription. The local and state managers are responsible for supplying OPMs, and they programme and regulate services and access for the population according to the identified needs,

respecting the pacts signed in the Pacted and Integrated Programming (PPI) and the terms of commitment to guarantee access. In this case, it is not necessary for the health service to be recognised by the Ministry of Health (MS) as a Specialised

Rehabilitation Centre (CER) in order to dispense OPMs.

In Bahia, the RCPD is governed by CIB/BA Resolution No. 167/2013 [8], which establishes state guidelines. According to the Bahia State Health Department (SESAB) [9], the specialised care component of the RCPD in Bahia comprises 25 services, 16 of which are specialised rehabilitation centres (CER) and nine of which are single rehabilitation establishments (EUR). These are distributed across nine health macro-regions in 22 municipalities within 16 health regions characterised by host municipalities [10], as shown in Figure 6.

In the Northeast health macro-region are the municipalities of Alagoinhas and Ribeira do Pombal. In the Central-East are Feira de Santana, Serrinha, Itaberaba and Seabra. In the West are Barreiras, Ibotirama and Santa Maria da Vitória. In the centre north, there are Irecê and Jacobina; in the south west, there are Vitória da Conquista,

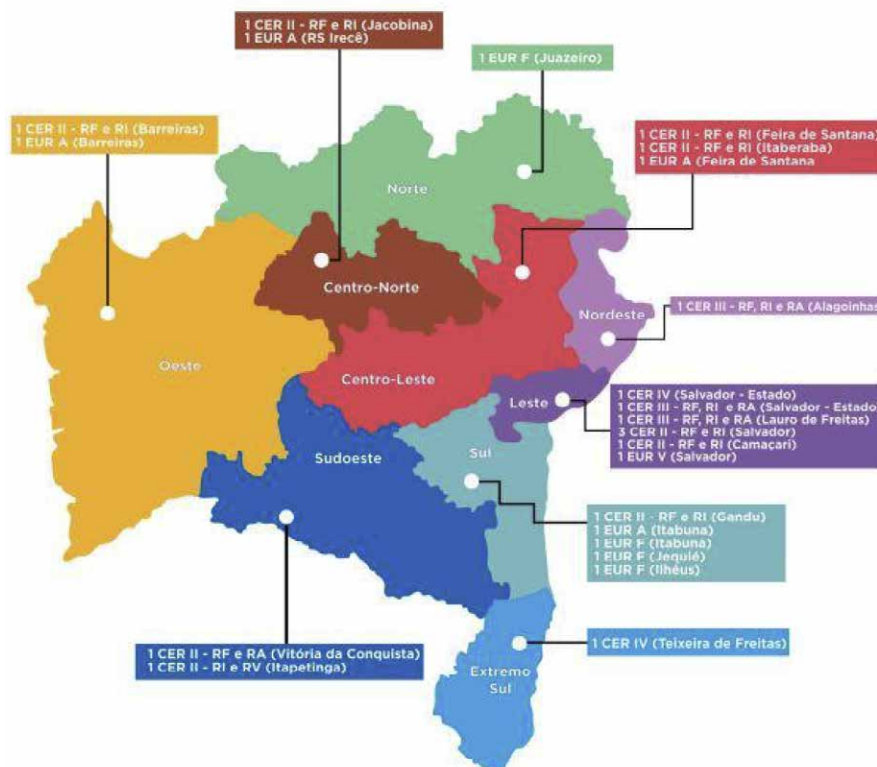
Itapetinga, Guanambi and Brumado; in the north, there are Juazeiro, Paulo Afonso and Senhor do Bonfim; in the south, there are Ilhéus, Itabuna, Jequié and Valença; in the far south, there are Porto Seguro and Teixeira de Freitas. In 2021, the National Register of Health Establishments (CNES) included an orthopaedic workshop linked to CER IV in Teixeira de Freitas, in the far south of Bahia. There is a care gap in Bahia due to the uneven distribution of orthopaedic workshops across the state and the limited provision of OPMs[11].

The Orthopaedic Workshop of Teixeira de Freitas was not included in the distribution of specialised rehabilitation care services covered by health regions.

The Provision of Prostheses in Bahia

The Technical Health Area for People with Disabilities (ATSPD) is responsible for formulating, monitoring and evaluating healthcare and

Figure 6. Specialized Rehabilitation Care Services by health region in Bahia.



Source: ATSPD/CPST/DGC/SAIS/SESAB, 2025

rehabilitation initiatives for people with disabilities across all nine Health Macro-Regions of Bahia [9,12]. The ATSPD's activities aim to provide institutional support to municipal managers for the prevention and early detection of disabilities, as well as comprehensive healthcare for people with disabilities. The ATSPD also participates in state committees and intersectoral working groups that plan and discuss comprehensive healthcare for people with disabilities. The ATSPD also implements the Network with the aim of setting up and implementing the RCPD in the various health regions, linking the points of care in the various components, and discussing the flow of users. The ATSPD makes efforts to implement the Network throughout the state of Bahia, including proposals to enable new Specialised Rehabilitation Centres (CERs) [9].

The panorama of prosthesis dispensation in Bahia mirrors the national situation. However, the difference in the quantities of lower limb and upper limb prostheses dispensed is striking, despite the respective differences in the number of amputations.

A total of 6.643 lower limb prostheses were dispensed, compared to 64 upper limb prostheses [7]. Upper limb prostheses account for 10,1% of upper limb amputations, whereas lower limb amputations account for 37%. Lower limb amputations are far more prevalent than upper limb amputations. As the field of upper limb prosthetics becomes increasingly technical and specialised, it is challenging for many prosthetists to expand their knowledge and applications since significantly fewer people with upper limb amputations are treated [13].

In the nine health macro-regions of Bahia, establishments are classified as either Specialised Rehabilitation Centres (CER) or Single Rehabilitation Establishments (EUR). However, the procedures for dispensing prostheses occurred in only five of these regions: Health Region (RS) Salvador (East); RS Feira de Santana (Central East); RS Jequié (South); RS Teixeira de Freitas (Far South); and RS Barreiras (West), as shown in Figures 7 and 8.

Figure 7. Dispensing of upper limb prostheses in Bahia: 2020-2024:

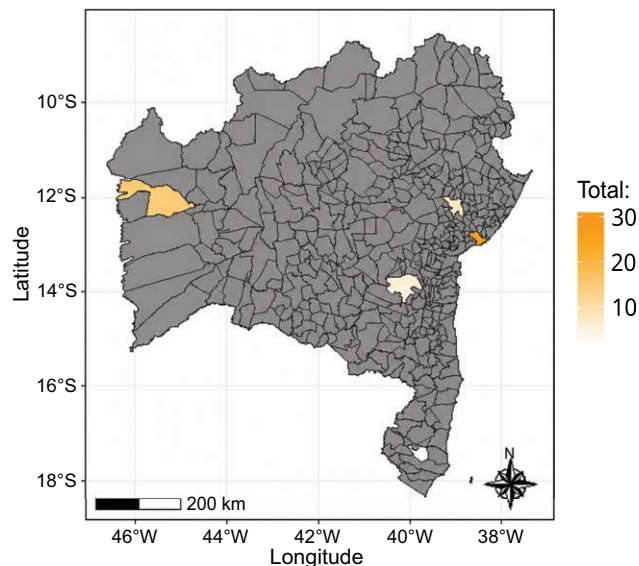
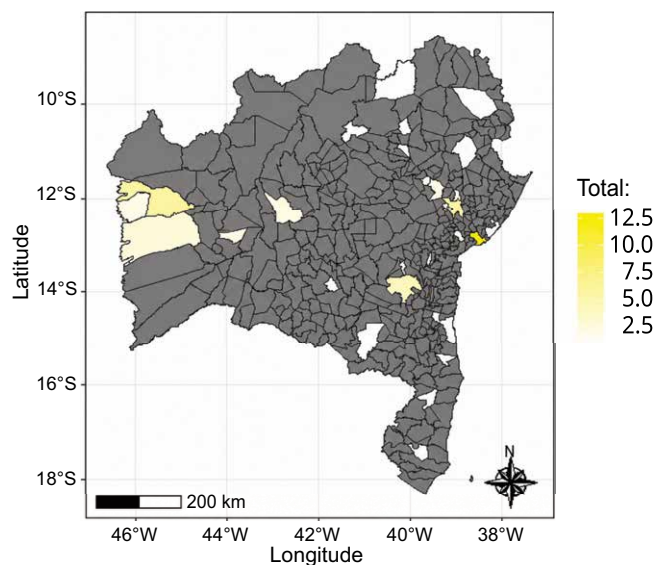


Figure 8. Dispensing procedures for upper limb prostheses in Bahia by municipality of residence: 2020-2024



The establishments with the highest number of dispensations are the State Centre for the Prevention and Rehabilitation of Disabilities (Cepred) (29), the Specialised Centre for the Rehabilitation of People with Disabilities (Anibal Alves Filho) (16), and the Feira de Santana Association for the Education and Care of People with Intellectual Disabilities (APAE) (9).

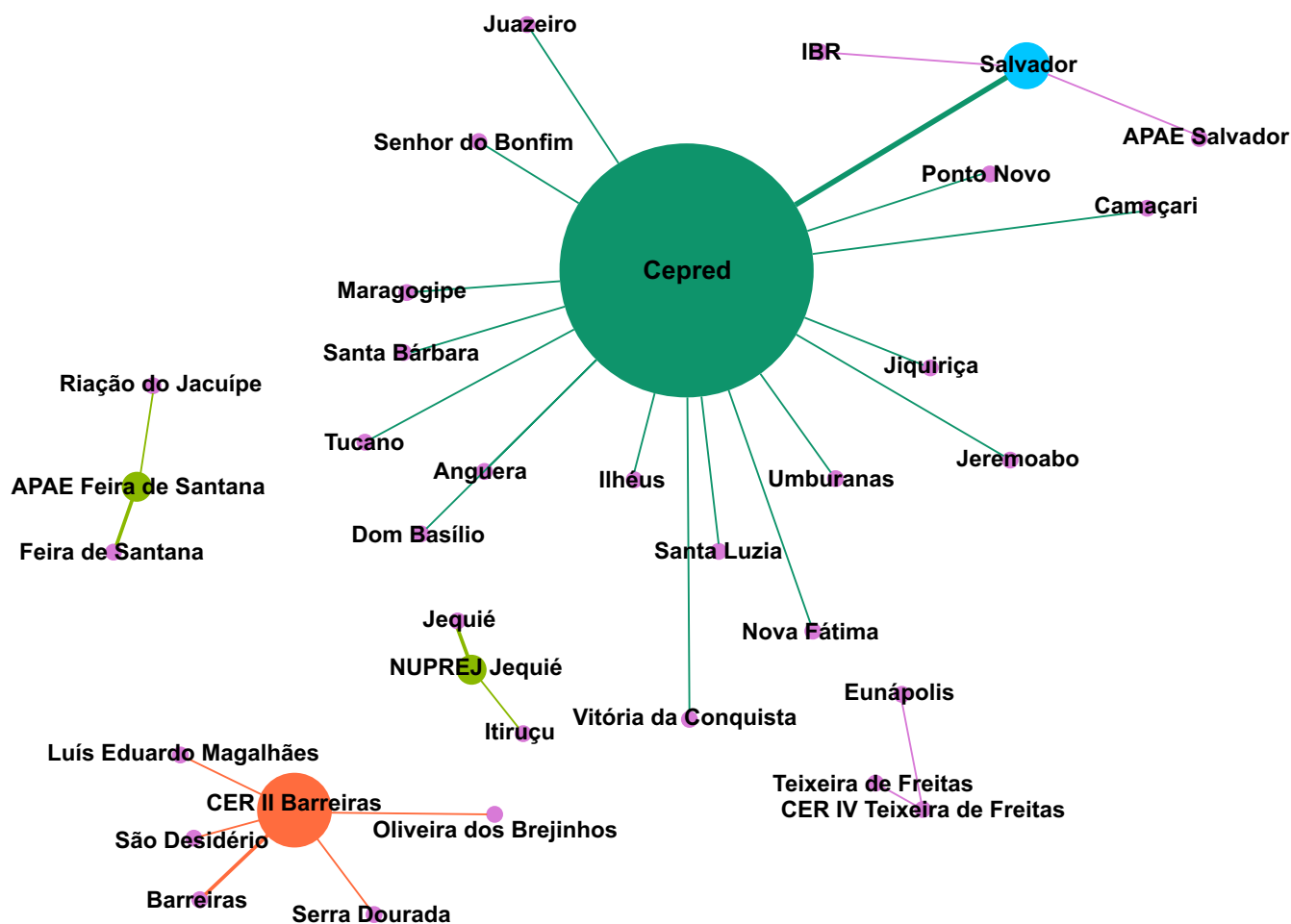
Figure 9 shows the representation of the flow of demand, municipality of origin and destination of the health establishment.

The State Centre for the Prevention and Rehabilitation of People with Disabilities (Cepred) is a unit of the Unified Health System (SUS). Founded in 1998 and located in the city of Salvador, Bahia, it is accredited as a Specialised Rehabilitation Centre (CER III). It carries out secondary prevention and rehabilitation activities for people with physical, hearing, intellectual, ostomy and multiple disabilities. It forms part of the RCPD of the State of Bahia and is based on the theoretical foundations of the Ministry of Health Programme and the Healthcare Programme for People with Disabilities of the State Health Department (SESAB).

Although Cepred is the largest dispensing centre for upper limb prostheses, the high demand from the various regions of the state exceeds the unit's installed and technical capacity, as set out in the Assistance Regulation [14] for the Granting of Prostheses. This generates longer delays in the provision of a range of services [15].

A possible process for dispensing prostheses begins with the patient's initial visit to a Basic Health Unit (UBS) for an initial assessment and referral to specialised services within the health macro-region. Depending on the complexity of the service required, the patient may be redirected to another reference centre, such as Cepred. Examples of greater complexity include: bilateral amputations; difficult-to-heal stumps (requiring more than four months of rehabilitation); stumps

Figure 9. Municipality (origin) and health establishments (origin) in the State of Bahia 2020 - 2024.



Source: Prepared by the author based on DATASUS/SIH/SUS, 2025.

with deformities requiring specialised prostheses; wrap-around prostheses; and hip disarticulation prostheses [15].

Multi-professionals, such as doctors and physiotherapists, carry out assessments and referrals. They assess the need for prostheses and refer patients to the CER, EUR or Orthopaedic Workshops. Depending on stock availability and the order of registration, patients are registered and included on a waiting list for the prosthesis. Once the prosthesis has been evaluated and manufactured, the patient is called to receive it, after which rehabilitation routines begin.

Discussion

Given the challenges associated with providing prostheses in Brazil, the disparity in the number of dispensations across different prosthesis categories, and the uneven distribution across the state of Bahia's health macro-regions, exploring solutions to improve production processes and access to assistive technologies is crucial.

Accessing prostheses late can lead to greater difficulty in accepting and rehabilitating [16]. These delays can directly affect the rehabilitation process and even hinder the amputee's social and economic reintegration, preventing them from participating fully and effectively in society on an equal footing with others [6].

To effectively implement the RCPD throughout the state, progress must be made in overcoming the inequalities between central-level network management actions and those developed in the health regions. This will ensure that all network operational phases are completed, providing articulation of all network components to effectively expand access and improve care quality in the direction of integrality [17].

As a public policy of specialised care for patients with disabilities [18], the CERs and Orthopaedic Workshops are not distributed equitably across the territory. Gaps in care should be taken into account when planning or expanding activities, particularly with regard to the provision of upper limb prostheses.

One way to avoid possible delays could be to use digital manufacturing [19] to produce prostheses. This involves using 3D modelling and printing to develop assistive technology.

Conclusion

The pathways for dispensing prostheses in the state of Bahia are supported by the State Action Plan for the Care Network for People with Disabilities. However, solutions are needed to speed up access to prostheses for amputees.

Although the State Action Plan for the Care Network for People with Disabilities has implemented regionalised coverage by Specialised Rehabilitation Centres (CER) and Single Rehabilitation Establishments (EUR) in Bahia, there is still unmet demand. For example, there is a need for prosthesis dispensing services in health territories to avoid patients having to move to other health macro-regions.

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Smart and Inclusive Cities: Challenges and Perspectives for Aging in Salvador, Bahia

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This article explores the intersection between smart cities and the challenges posed by global population aging, with a focus on the city of Salvador, Bahia. It addresses whether current smart city initiatives are genuinely inclusive and human-centered, especially for the elderly. Drawing on updated data from the United Nations, IBGE, and WHO, combined with a bibliographic review of recent studies, the methodology follows a documentary and exploratory approach that allows for the correlation between demographic indicators, smart city rankings, and the WHO age-friendly city framework. The study highlights demographic shifts and the accelerated aging process in Brazil, which demands urgent adaptations in public infrastructure, healthcare, and digital inclusion. The concept of age-friendly cities, guided by the WHO framework, is used to discuss strategies that support active aging, emphasizing mobility, accessibility, social participation, and technological access. The paper also examines the role of smartphones and wearable health-monitoring technologies in promoting digital inclusion and improving the quality of life for elderly citizens, even when direct interaction with devices is limited. Salvador ranks highly in national smart city indices, particularly among northeastern capitals, yet falls behind in key indicators for elderly support, such as health and accessibility. Although some efforts are underway — such as adapted public transport and metro systems — structural urban barriers persist. The analysis concludes that while Salvador has the potential to evolve into a model of an inclusive smart city, significant gaps remain in aligning technological innovation with the social and human dimensions of aging. Bridging this gap will require coordinated public policies, community engagement, and a redefinition of what “smart” truly means in a society increasingly shaped by its older population.

Keywords: Smart Cities. Population Aging. Age-Friendly Cities. Digital Inclusion.

The concept of smart cities has received growing attention in recent decades, particularly in the context of the digitalization of urban spaces. However, the question remains: can such cities be considered truly humane and inclusive? [1]. This study is based on this issue, seeking to analyze the limits and potential of smart cities in the face of population aging and digital inclusion. This article was prepared based on data from the Brazilian Institute of Geography and Statistics (IBGE), where we bring recent data from the 2022 Census,

in addition we seek data from the World Health Organization (WHO), the Global Guide to Age-Friendly Cities, Urban Systems, with the Ranking of Smart Cities, in addition to a bibliographic survey of articles from 2020 to 2024.

Accordingly, this study employs a methodology grounded in documentary analysis and bibliographic review, combining official statistical data with recent literature to correlate urban indicators, population aging, and the challenges of digital inclusion.

In the context of care for the elderly, smart cities can play a strategic role by implementing solutions such as remote health monitoring, fall detection, accessible transportation, and adapted public lighting. By using real-time data and Internet of Things (IoT) devices, it becomes possible to guarantee greater safety and autonomy

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for the elderly who live alone, in addition to also supporting family members, caregivers, and public services in making faster and more effective decisions, promoting active aging and social inclusion. This study is organized into the following sections: Section 2, Methodology. Here, we justify the choice of the applied methodology and provide a brief explanation. Section 3, Population aging. Here we bring statistical data about the elderly population from institutions such as IBGE and the World Health Organization (WHO), in addition to reflecting on the topic; Section 3.1 - Age-Friendly Cities. We explain the concept according to the WHO and reflect on it; Section 3.2 - Smart Cities. Here we bring the concept and reflect on it from the perspective of several authors, in addition to establishing a convergence with the concept of Age-Friendly Cities. Finally, Section 4 - Conclusion, where we reflect on the topic for the city of Salvador, State of Bahia.

Materials and Methods

This study adopts an exploratory and qualitative approach, structured through a bibliographic review (articles published between 2020–2024) and documentary analysis of official reports and databases (IBGE, WHO, Urban Systems, ISO).

This methodological design made it possible to examine the interactions between demographic aging, smart city indicators, and the WHO framework for age-friendly cities, enabling the identification of both gaps and opportunities in the specific case of Salvador.

Population Aging

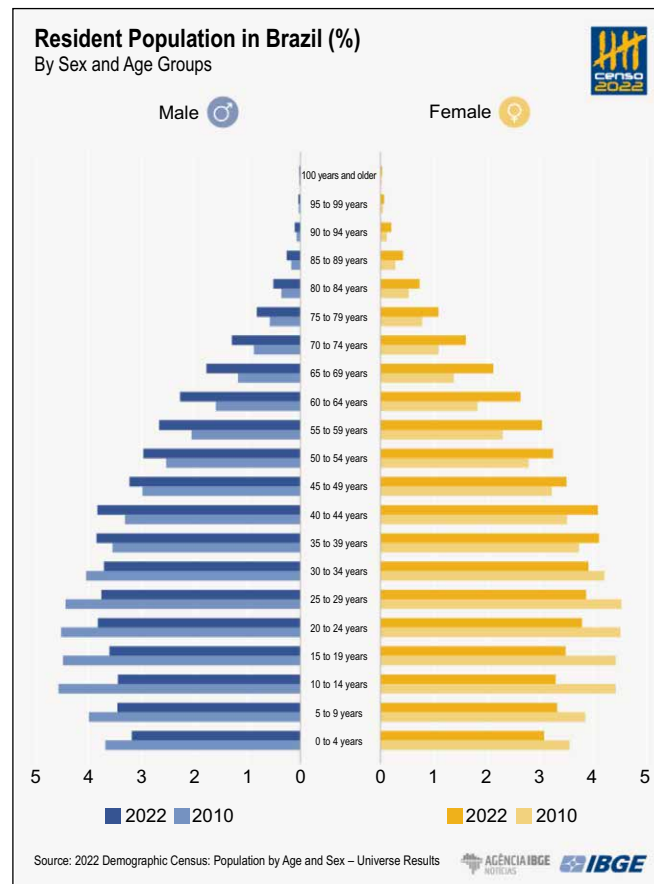
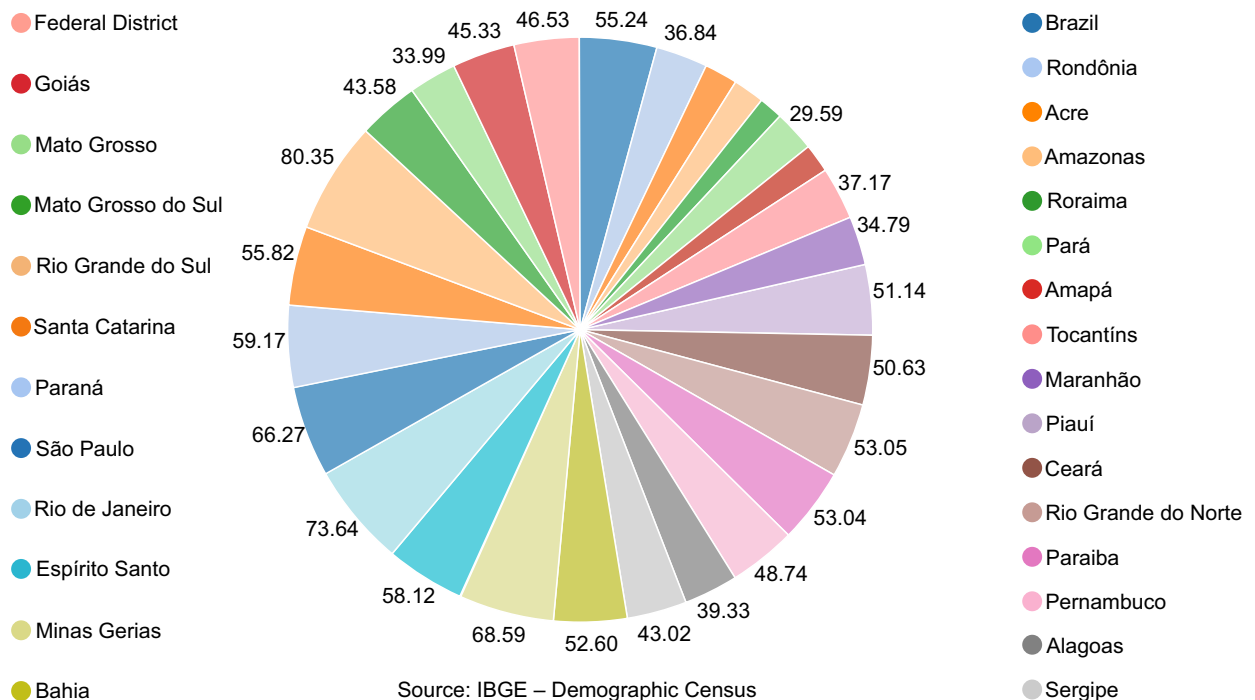
According to the IBGE [2], the population of people aged 65 or older increased by 57.4% between the 2010 and 2022 censuses. This represents 10.9%. The graph in (Figure 1) shows a narrowing at the base of the Brazilian age pyramid, which is accentuated between the years 2010 and 2022, indicating an aging of the population in recent years.

According to the World Health Organization (WHO) [3], the global population aged 60 or over reached 1 billion in 2020 and is projected to reach 1.4 billion by 2030 and 2.1 billion by 2050, representing the fastest growth in history. Furthermore, according to the WHO [3], the number of people aged 80 or over is expected to triple between 2020 and 2050, reaching 426 million. Since 2015, the proportion of individuals over 60 is expected to increase from 12% to 22% by 2050, with 80% of this group residing in low- and middle-income countries.

According to Li and colleagues [4], in Latin America and the Caribbean, 13.1% of the population was aged 60 or older in 2021, with a projection to reach 20.6% by 2050, showing a continuous process of demographic aging. The authors emphasize that countries like Brazil, Chile, and Argentina have an accelerated pace of population aging, which requires significant adaptations in areas such as health, social security, and the provision of social services.

In the Brazilian context, the population aging process presents significant differences between the states, reflecting historical and structural regional inequalities. According to data from the IBGE [2], the national average aging rate reaches 52.24%, revealing that more than half of the Brazilian population is already in advanced age stages when considering the aging index. However, this average hides significant disparities: the state of Rio Grande do Sul has the highest rate in the country, 80.35%, showing a strongly aged population structure, resulting from a combination of factors such as low fertility and higher life expectancy. In contrast, states in the Northeast, such as Bahia, have more moderate rates, 52.60%, but which still signal a growing trend of aging, with direct implications for public policies in areas such as health, social security, and social assistance (Figure 2).

This regional variation raises reflections on the challenges of public management in the face of Brazil's demographic heterogeneity. Regions with a more aged population require greater attention to specialized health services, urban adaptation,

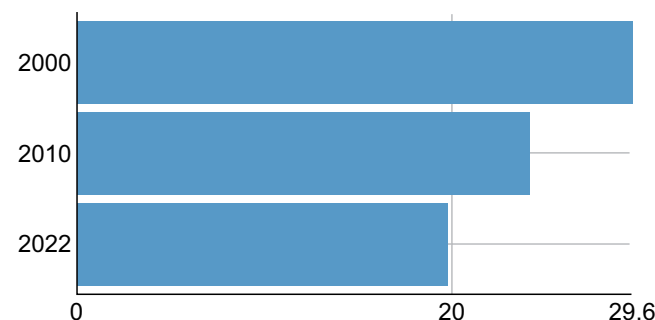
Figure 1. Brazilian age pyramid (2010-2022).**Figure 2.** Brazil and Federative Units – Aging Rate (2022).

and social inclusion strategies for the elderly. In contrast, states with intermediate rates, such as Bahia, are in a phase of demographic transition that requires preventive planning to avoid future overload on social protection systems.

Observing the local context, according to the IBGE [2], the population of people aged 65 or over in Bahia increased by 48.5% compared to the 2010 census. At the time, this population was equivalent to 7.2% of the population, and by 2022, it already represented 10.6%. This significant difference shows that the population is also growing in our state.

Paralleling the growth of the elderly population, there is a significant reduction in the proportion of people aged 0 to 14 in Brazil, a phenomenon that highlights the advance of the country's demographic transition. In 2000, this age group represented 29.6% of the total population; in 2010, it dropped to 24.08%, and in 2022, it reached only 19.76% (Figure 3).

Figure 3. Brazilian population aged 0 to 14 (2022).



Source: IBGE – Demographic Census

The continuous decrease of this age group results in a progressive narrowing of the base of the age pyramid, signaling that the country is moving towards an aged population structure. This phenomenon has direct implications for the planning of public policies, especially with regard to the reorganization of investments in basic education, social security, and health, in addition to alerting to the future impact on the workforce and the sustainability of social protection systems. This is a problem not only for public bodies but for all of civil society.

Age-Friendly Cities

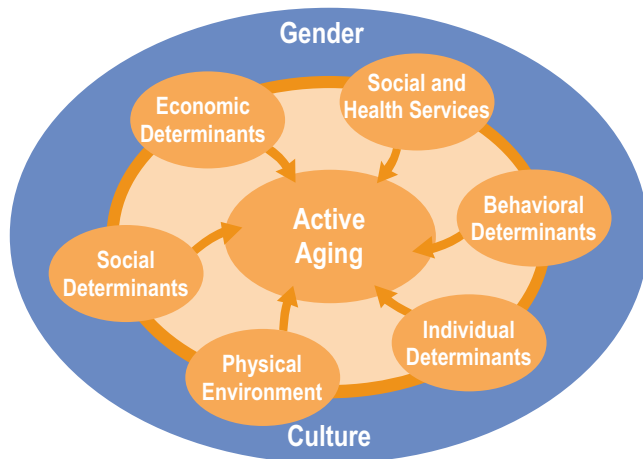
The "Age-Friendly Cities" is a global project whose main objective is to respond to questions of contemporary, daily urban life [5]. According to the WHO's Guide to Age-Friendly Cities[3], policies, services, settings, and structures should support active aging by:

- 1) Recognize the wide range of older people's abilities and services;
- 2) Respond to the needs and preferences of older people;
- 3) Respect individual lifestyle decisions and choices;
- 4) Protect the most vulnerable;
- 5) Promote the inclusion and contribution of these individuals in all aspects of community life.

According to the World Health Organization (WHO) guide[5], active aging results from a dynamic interaction among multiple determinants that act throughout life. Among them, individual factors stand out, such as biological and behavioral characteristics, family and community contexts, and social and economic determinants, which include conditions of income, education, and access to services. The combination of these elements, interacting continuously, has a decisive influence on how each individual experiences the aging process, which can favor or limit their autonomy and quality of life. Furthermore, according to the WHO's Guide to Age-Friendly Cities[3], these cities should incorporate many of these aspects into their characteristics (Figure 4).

According to Duque and Oliveira [6], this guide chooses eight aspects of urban life: outdoor spaces and buildings; transportation; housing; social participation; respect and social inclusion; civic participation and employment; communication and information; and community support and health services (Figure 5).

The authors conclude that although these aspects are linked and directly influence one another, transportation, communication, and information have a strong influence on active aging in the city.

Figure 4. Determinants of active aging.**Figura 5.** Axes of the global age-friendly cities guide – Aspects of urban life.

Smart Cities

When discussing smart cities, concepts such as the Internet of Things (IoT), Artificial Intelligence (AI), and the Internet emerge as the focus of enabling technologies[1]. However, technology is not the only necessary tool for a city to be considered intelligent. Other factors must be taken into account.

According to the International Organization for Standardization (ISO) [7], the evaluation of smart cities is based on 80 indicators distributed across

different dimensions, such as Sports and Culture, Urban Planning, Environment and climate change, among others. Although these parameters allow for the ranking of municipalities, their placement does not always fully reflect the quality or effectiveness of local public policies, sometimes revealing discrepancies between numerical performance and urban reality.

The municipality of Salvador, the capital of Bahia, holds the sixth position among Brazilian capitals in the 2024 smart cities ranking, according to a report by Urban Systems[8], which evaluated 100 municipalities. Considering the overall ranking, which includes cities of different sizes, Salvador achieved the tenth position and first in the Northeast, standing out in indicators such as technology (7th), economy (8th), and mobility (14th).

Despite this favorable performance, such a classification does not guarantee that the city is effectively inclusive, since urban intelligence indicators do not, by themselves, reflect the capacity to equitably meet the needs of the entire population. This is because the criteria adopted for evaluating smart cities generally prioritize technological indicators, such as digital infrastructure, connectivity, and the adoption of innovative solutions for urban management. However, social inclusion, understood as equitable access to services and the effective participation of historically marginalized groups, demands a more in-depth analysis.

According to Caragliu, Del Bo, and Nijkamp [9], a smart city is one that invests in human and social capital, communication infrastructure, and sustainable development to promote economic growth and quality of life, with participatory governance. This concept, which defines a smart city, leads us to the idea of an inclusive, technological city that facilitates citizen mobility, with respect for the environment and its citizens. However, this is a topic to be studied and discussed.

Fernandes [1] conducted a study on inclusion in smart cities. To do this, he performed a literature review with various authors who discuss the topic. From this study, the author concludes that

social inclusion is a fundamental factor and can be achieved through digital inclusion, but digital inclusion is affected by the lack of access to technology.

For Soja [10], spatial justice is fundamental to address the socio-spatial inequalities that permeate the urban environment, ensuring that all citizens have fair access to available resources and opportunities. Complementarily, Sen's capability approach[11] emphasizes that social inclusion should be understood in terms of the real opportunities individuals have to develop their potential and participate fully in community life, which goes beyond simple physical access to urban spaces.

Thus, the assessment of urban intelligence must be complemented by social and spatial indicators that allow for a broader understanding of the conditions of inclusion, ensuring that technological development goes hand in hand with the promotion of social justice and equity. The use of smartphones has been a great ally of smart cities, especially in terms of communication and accessibility. Through this device, people communicate with relatives and friends while keeping themselves informed[12]. In a study conducted in the city of Santa Cruz do Sul, in the interior of Rio Grande do Sul, Tilvtz and Areosa[12] found that 64% of seniors who own smartphones do not know how to use the device, while 12% do not even have one. In another survey with 230 elderly people, Borges and colleagues [13] concluded that the most used medium to access the internet is the cell phone, accounting for 76.5% of the total sample, which demonstrates a significant number of seniors who already have access to mobile technologies. In the context of smart cities, mobile devices are important for the inclusion of elderly citizens, but there are also other technologies. An approach to wearable systems for monitoring the elderly, such as that proposed by Sanfilipo and Pachierotti[14] and Elahi and colleagues[15], involves the use of portable ECG, temperature sensors, and other sensors, associated with the use of artificial intelligence, and aims to reduce hospitalizations and improve quality of life. In this approach, there is a two-way street, as these

technologies rely on others, such as communication technologies, whether WiFi or 5G. In this way, there is an inclusion of the elderly, even if they do not interact directly with these devices or need to deeply understand their operation, but they can count on an improvement in quality of life and health.

But technology is not the only enabler of a smart city; quality of life, mobility, urbanization, and other elements, even if somehow linked to technology, can be analyzed separately.

Leisure is an important source of well-being and quality of life, and for this reason, it is present in smart cities[16]. Salvador, being a coastal city, has a rich source of leisure, which are the beaches. Although public and with free access to all people, Vila Verde and colleagues[16] report accessibility problems that hinder free movement for the elderly or people with mobility difficulties. The main problems reported by the authors include uneven, damaged, or illegally occupied sidewalks, as well as issues related to transportation, such as a low fleet of adapted buses on the waterfront circuit. The lack of public restrooms and signage was also identified.

Given the above, it becomes possible to establish a convergence between the concepts of Smart Cities and Age-Friendly Cities. Both models share the goal of promoting more inclusive, safe, and functional urban environments and find in technology and information strategic tools to enable the structural axes proposed by the guide. By integrating technological solutions with the perspective of active aging, the cities' capacity to efficiently respond to contemporary demographic and social challenges is strengthened.

Conclusion

Salvador holds a relevant position in the national ranking of smart cities, demonstrating the potential to use technology and information to implement solutions aimed at mobility, urban monitoring, and improving the quality of life for the elderly population. However, the capital of Bahia is not yet part of the Age-Friendly Cities network, according to the Global Age-Friendly Cities Guide[5]; in

Brazil, only Rio de Janeiro has this certification.

This discrepancy reveals that, although Salvador has technological infrastructure and some accessibility initiatives, such as adapted subways and buses, there is still a lack of integrated public policies and projects that guarantee broad and equitable coverage. To move towards a truly inclusive city, it is essential to articulate the principles of a smart city with the structural axes of an age-friendly city, promoting urban environments capable of ensuring safety, autonomy, and social participation for everyone, especially for the growing elderly population.

The analysis shows that Salvador's potential as a smart city has not yet fully translated into benefits for its elderly population. The absence of certification as an Age-Friendly City indicates that the available technological infrastructure is not enough on its own: it is necessary to convert it into effective public policies capable of promoting accessibility, safety, and quality of life.

The convergence between the principles of smart cities and the structural axes of age-friendly cities therefore represents a strategic opportunity for the urban environment to be inclusive and adapted to the ongoing demographic transition. This integration not only strengthens the commitment to active and healthy aging but also prepares the city for the social challenges that accompany the accelerated process of population aging.

These conclusions were made possible through the integrated analysis of official data and specialized literature, a methodology that not only mapped demographic aging but also critically assessed smart city indicators in light of the specific demands of the elderly population.

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Bibliometric Analysis of Inhibitory Compounds in the Reduction of Enteric Methane in Ruminants: Trends, Advances and Sustainable Perspectives

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Enteric fermentation is a major agricultural source of methane (CH₄), accounting for about 32% of anthropogenic emissions and contributing significantly to global warming. Research increasingly investigates natural and synthetic inhibitory compounds in ruminant diets to reduce emissions without compromising digestion or productivity. This work presents a bibliometric analysis of studies published between 2005 and 2025, using the *Web of Science* (WoS) database and 20 keywords in four thematic categories combined with Boolean operators. Of 1,058 publications retrieved, 115 met the co-occurrence criteria. Analysis with *VOSViewer*® identified five key research areas, including rumen physiology, nutritional strategies, and bioactive compounds, with strong alignment to Sustainable Development Goals (SDGs), particularly Climate Action. Publication trends show marked growth since 2020, underscoring the topic's rising scientific and societal relevance. The results position methane mitigation in livestock as a research priority, supporting the development of sustainable production pathways. **Keywords:** Ruminant. Inhibitory Compounds. Enteric Methane. *In vitro*. Agroindustrial By-products.

In 2022, the IPCC estimated that enteric fermentation emitted 118 Tg CH₄, representing 32% of anthropogenic methane. FAO and UNFCCC inventories show a ~20% variation due to different reporting methodologies, highlighting underestimation and the need for harmonization. The livestock sector remains a major global methane source [1,2].

In the rumen, cellulolytic bacteria degrade fibrous carbohydrates into volatile fatty acids, releasing H₂, which methanogenic archaea (mainly *Methanobrevibacter* spp.) use to reduce CO₂ to CH₄, expelled mainly by eructation [3]. Diet composition influences the acetate:propionate ratio, affecting hydrogen availability and methane output. Inhibitory compounds, natural or synthetic, reduce methanogenesis by inhibiting archaea, redirecting hydrogen, or altering substrate degradation [4], [5,6].

Natural options like tannins, saponins, pectin, and essential oils have shown potential to lower

methane without harming digestion, while synthetic additives such as nitrate, 3-NOP, and brominated algae expand mitigation strategies [2,6,7].

This study conducts a bibliometric analysis of inhibitory compounds in ruminant feed to assess trends and opportunities for reducing methane while maintaining productivity.

Materials and Methods

The research was based on a bibliometric analysis, aiming to identify collaborative trends and emerging patterns in the respective scientific field, considering the last 20 years, from 2005 to 2025, specifically until July 2025. The database used was Web of Science (WoS), due to its scope and relevance as a scientific database, where descriptors were assigned in four categories, (I) *Animal*: “Ruminant”, “Rumenferment”, “Rumenmicrobio”, “Methanogen archaea”, “microorganism”, (II) *Biology*: “Inhibit”, “Redoxpotential”, “Methane”, “Carbon sequest”, “Methane mitigation”, (III) *Analytical Methodologies*: “ampts”, “Batch ferment”, “Methane quantif”, “Anaerobic digestion”, “In vitro ferment”, (IV) *Raw Material*: “Orange peel”, “Cacao pod husk”, “pectin”, “Phenolic compound”, “Hesperidin”, with an

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emphasis on compounds that inhibit methane production in ruminants. Using Boolean operators “AND” and “OR” to formulate the search phrase, multiple combinations between categories were created, according to the Table 1.

The research focused on articles, including studies, conferences, and review articles from *Web of Science* (WoS). The search was refined to titles, keywords, and abstracts, resulting in more accurate data. *VOSviewer*® software was used to analyze and visualize the thematic groups and clusters.

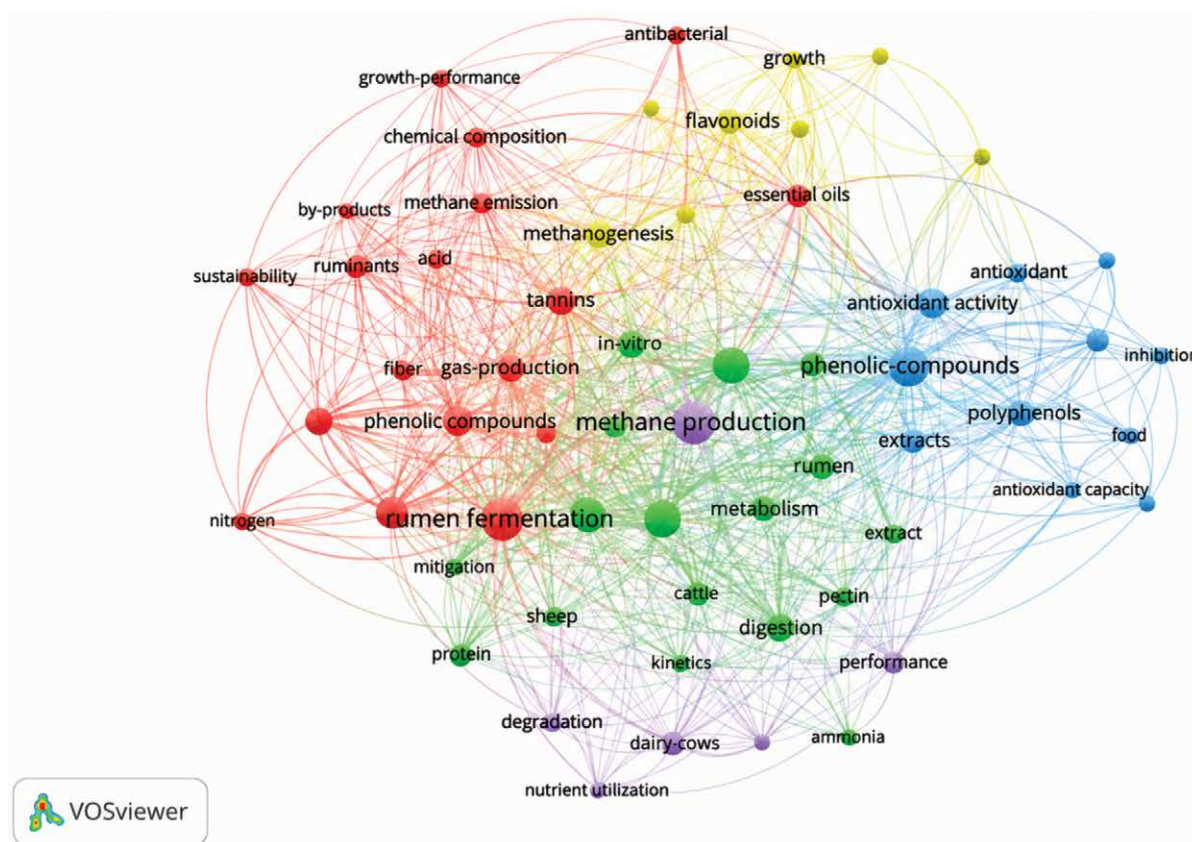
Results and Discussions

The analysis of 1,058 publications retrieved from the WoS database identified 115 articles meeting all three thematic co-occurrence criteria. Thematic focus and predominant approaches were examined through a keyword co-occurrence network (Figure 1), organized into five clusters representing the core research axes on enteric fermentation and sustainability.

The Red Cluster forms the structural core, integrating terms such as “rumen,” “fermentation,” “methane emission,” and “gas production,” which describe the physiological basis of methanogenesis, alongside “tannins” and “phenolic compounds,” indicating the role of natural compounds in environmental mitigation. The Green Cluster combines “digestion,” “metabolism,” “cattle,” and “sheep,” reflecting interspecies comparisons, while “protein,” “pectin,” and “kinetics” highlight nutritional optimization, and “performance” with “mitigation” indicate the challenge of balancing productivity and emission reduction. The Blue Cluster links “antioxidant activity,” “polyphenols,” and “inhibition,” signaling the potential of bioactive compounds for microbial control and animal health via “extracts” and “food.” The Yellow Cluster connects “flavonoids,” “essential oils,” and “antibacterial” with “methanogenesis” and “*in vitro*,” supporting their role as methane inhibitors, with “growth” suggesting systemic effects. The smaller Purple Cluster associates “methane

Table 1. Keyword combination.

Search Line	Combination	Description
7	#1 AND #2 AND #3 AND #4	(“Ruminant*” OR “Rumen ferment*” OR “Rumen microbio*” OR “Methanogen archaea*” OR “microorganism*”) AND (“ampts*” OR “Batch ferment*” OR “Methane quantif*” OR “Anaerobic digestion*” OR “ <i>In vitro</i> ferment*”) AND (“Inhibit*” OR “Redox potential*” OR “Methane*” OR “Carbon sequest*” OR “Methane mitigation*”) AND (“Orange peel*” OR “Cacao pod husk*” OR “pectin*” OR “Phenolic compound*” OR “Hesperidin*”)
9	#1 AND #2 AND #4	(“Ruminant*” OR “Rumen ferment*” OR “Rumen microbio*” OR “Methanogen archaea*” OR “microorganism*”) AND (“Inhibit*” OR “Redox potential*” OR “Methane*” OR “Carbon sequest*” OR “Methane mitigation*”) AND (“Orange peel*” OR “Cacao pod husk*” OR “pectin*” OR “Phenolic compound*” OR “Hesperidin*”)
10	#1 AND #3 AND #4	(“Ruminant*” OR “Rumen ferment*” OR “Rumen microbio*” OR “Methanogen archaea*” OR “microorganism*”) AND (“ampts*” OR “Batch ferment*” OR “Methane quantif*” OR “Anaerobic digestion*” OR “ <i>In vitro</i> ferment*”) AND (“Orange peel*” OR “Cacao pod husk*” OR “pectin*” OR “Phenolic compound*” OR “Hesperidin*”)

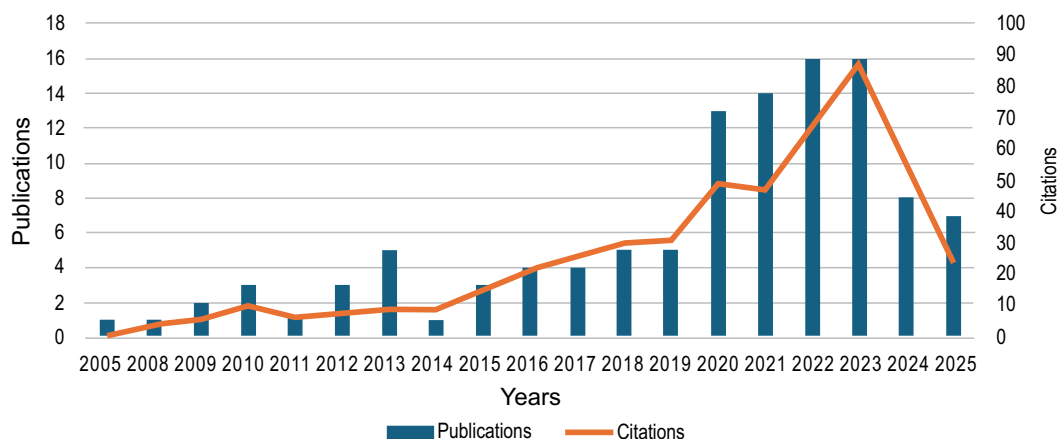
Figure 1. Representation of the keyword network and correlation of the most relevant themes.

production” and “dairy cows” with “degradation,” “ammonia,” and “nutrient utilization,” pointing to precision nutrition strategies. Overall, research is concentrated on physiological mechanisms and environmental mitigation (Red and Green), with complementary approaches exploring bioactive solutions (Blue/Yellow) and targeted nutritional management (Purple).

Scientific output trends (Figure 2) show modest, irregular publication rates between 2005 and 2014 (1–5 papers/year, <10 citations/year), with occasional peaks (e.g., 2013). From 2015, publication numbers rose steadily, with citations surpassing 30 in 2019. A major increase occurred in 2020 (13 papers, 49 citations), followed by sustained high output through 2023 (16 papers, 88 citations). Together, 2020–2023 account for over half of the analyzed output. The apparent decline in 2024–2025 likely reflects incomplete indexing. These trends indicate growing relevance of methane

mitigation research for ruminants, sustainability, and climate change.

Analysis of Sustainable Development Goal (SDG) alignment (Figure 3) reveals a predominance of environmental goals, especially SDG 13 – Climate Action (72 publications, 62.6%), linked to Target 13.2 through emission mitigation and adaptation in agriculture. Other relevant goals include SDG 12 – Responsible Consumption and Production (15; Target 12.3), via agro-industrial waste valorization; SDG 7 – Affordable and Clean Energy (13; Target 7.2), via methane-to-biogas conversion; and SDG 6 – Clean Water (implicit; Target 6.3) through effluent management. Social goals are led by SDG 3 – Good Health and Well-being (19; Target 3.9), focusing on animal health and reduced antibiotic use, and SDG 2 – Zero Hunger (2; Target 2.4), promoting sustainable food systems. SDG 11 – Sustainable Cities (1; Target 11.6) addresses waste management. Eight

Figure 2. Several publications and citations vs. years.**Figure 3.** The most common sustainable development goals.

Sustainable Development Goal	Record Count	Percentage
 13 Climate Action	72	62.61%
 03 Good Health And Well Being	19	16.52%
 12 Responsible Consumption And Production	15	13.04%
 07 Affordable And Clean Energy	13	11.30%
 06 Clean Water And Sanitation	12	10.44%
 02 Zero Hunger	2	1.74%
 14 Life Below Water	2	1.74%
 11 Sustainable Cities And Communities	1	0.87%
 Do not contain data in the field being analyzed	8	6.96%

publications were technical/methodological without direct SDG linkage.

The 20 most relevant and cited studies are summarized in Table 2, with objectives and associated clusters from Figure 1. While most address enteric fermentation, others focus on anaerobic digestion of lignocellulosic biomass or agro-industrial residues. Notable works [9, 11, 12, 14] expand biochemical and microbiological understanding

of methanogenesis and its mitigation. The breadth of approaches highlights the interdisciplinarity of the field and points to promising, sustainable innovations for animal production.

Conclusion

Over the past two decades, research on enteric methane mitigation in ruminants has grown steadily,

Table 2. Comparative table of the 20 most relevant and cited articles.

Authors	Study Objective	Associated Cluster and Keyword
[9]	To assess the enzymatic potential for the valorization of agro-industrial by-products.	Blue: Bioactive compounds (“polyphenols”, “enzymes”).
[10]	To evaluate the effect of including tannins, pectin, and polyethylene glycol in rumen fermentation, aiming to reduce the negative impacts of tannins on microbiota and gas production.	Red and Green: Methanogenesis physiology (“tannins”) and nutritional optimization (“pectin”).
[11]	To optimize orange peel waste ensiling for sustainable anaerobic digestion, evaluating d-limonene removal.	Yellow and Blue: Essential oils (“essential oils”) and antimicrobial activity (“antioxidant activity”).
[12]	To evaluate the integration of pyrolysis and anaerobic digestion in the conversion of lignocellulosic biomass into methane.	Purple and Red: Application in dairy cow nutrition (“methane production”) and methanogenesis (“methane production”).
[13]	To review lignocellulosic biomass liquefaction for methane production via anaerobic digestion.	Red and Purple: Methanogenesis (“methane production”) and dairy cow nutritional management (“nutrient utilization”).
[14]	To evaluate carbohydrate sources and protein degradability on lactation, rumen fermentation, and blood profile in dairy cows.	Green and Purple: Nutritional optimization (“protein”, “pectin”) and precision feeding in dairy cows (“dairy-cows”).
[15]	To evaluate the antimicrobial and antioxidant activity of pomegranate, orange, and banana peel extracts.	Blue: Antioxidant bioactive compounds (“antioxidant activity”).
[16]	To evaluate the expression of bacterial genes in the rumen related to methane emission, linked to methyl compound production.	Red and Purple: Methanogenesis (“methane emission”) and specific nutritional management (“nutrient utilization”).
[17]	To evaluate the effect of biochar in the anaerobic digestion of citrus residues, focusing on microbial communities and methane production.	Purple and Green: Precision nutrition (“dairy-cows”) and digestive optimization (“metabolism”).
[18]	To investigate the effect of phloroglucinol on rumen fermentation and methane emissions.	Blue and Red: Microbial inhibition (“inhibition”) and methanogenesis (“methanogenesis”).
[19]	To review the use of plant secondary metabolites as feed additives in calves, evaluating antimicrobial mechanisms.	Blue and Yellow: Bioactive compounds (“polyphenols”) and essential oils (“essential oils”).
[20]	To review the antibacterial mechanisms of plant phenolic compounds using systems biology.	Blue and Yellow: Phenolic compounds (“phenolic compounds”) and flavonoids (“flavonoids”).
[21]	To assess the antimicrobial activity of fruit peels against pathogenic bacteria and fungi.	Blue and Yellow: Bioactive compounds (“phenolic compounds”) and essential oils (“essential oils”).
[22]	To evaluate the effect of flavonoids (Bioflavex®) on rumen fermentation and <i>in vitro</i> methane production.	Red, Yellow, and Blue: Methanogenesis (“methanogenesis”), flavonoids (“flavonoids”), and bioactive compounds (“polyphenols”).
[23]	To evaluate the effects of essential oils on <i>in vitro</i> rumen fermentation, analyzing end products such as volatile fatty acids and ammonia.	Yellow: Essential oils in methanogenesis inhibition (“essential oils”).
[24]	To investigate the diversity of the intestinal archaeome in animals, analyzing its relationship with diet and intestinal physiology.	Red and Green: Methanogenesis physiology (“methane emission”) and nutritional optimization (“digestion”).
[25]	To evaluate the antifungal activity of orange peel essential oil against <i>Aspergillus flavus</i> , by direct contact and vapor exposure.	Blue and Yellow: Essential oils (“essential oils”) and antimicrobial activity (“antibacterial”).
[26]	To evaluate cashew nut shell liquid as a methane inhibition and propionate promoter in rumen fermentation.	Red, Blue, and Green: Methane inhibition (“methane-inhibiting”), phenolic compounds (“phenolic compounds”), and nutritional optimization (“propionate”).
[27]	To assess the effects of fermentation on the composition and bioactivity of polyphenols in fermented foods.	Blue and Red: Bioactive compounds (“polyphenols”) and fermentation processes (“fermentation”).
[28]	To produce single-cell protein through solid-state fermentation of orange waste, investigating synergistic microbial interactions.	Blue and Green: Bioactive compounds (“protein”) and nutritional optimization (“food”).

integrating physiology, nutrition, and biotechnology. Remaining gaps include standardization in bioactive compound use and economic viability assessments. Continued applied research is essential to develop efficient, sustainable nutritional strategies aligned with global environmental goals.

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Evaluation of Multiple Optimization Scenarios for Manual Parcel Handling Cells with a Focus on Increasing Productivity using FlexSim and Experimenter

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This article presents a systematic review of the literature on the use of simulation with FlexSim and Experimenter, focusing on manual parcel handling centers. The review aims to identify and analyze multiple simulation articles that address productivity improvement, idle time reduction, and process efficiency in manual operations. The methodology followed PRISMA guidelines, ensuring a structured process for study identification, screening, eligibility assessment and inclusion. The main literature findings indicate that simulation enables the evaluation of different scenarios and patterns, providing insights that, when combined with strategies such as Lean Manufacturing, lead to significant gains in productivity and efficiency. The studies reviewed reported productivity gains of up to 35% and reductions of up to 82% in operator travel time, demonstrating the potential impact of combining simulation with process improvement methodologies. It is concluded that the combined use of these tools not only allows the simulation of diverse scenarios but also facilitates decision-making and the development of innovative logistics solutions.

Keywords: FlexSim. Experimenter. Scenarios. Logistics Solutions.

In recent years, the demand for efficient logistics operations has grown exponentially, driven by the expansion of e-commerce and the need to optimize resources in a highly competitive market [1]. In the Brazilian context, the rapid growth of e-commerce has intensified the need for faster and more efficient logistics operations, creating pressure on parcel handling centers to adapt quickly.

In this scenario, where complex operations must be carried out quickly and accurately, the application of computer simulation techniques has emerged as a key approach to optimizing processes and increasing productivity. This context becomes even more relevant when operations involve manual parcel handling, which may present bottlenecks, time waste and resource allocation issues.

Simulation methodologies, particularly with FlexSim software and its Experimenter tool, allow the modeling and assessment of multiple scenarios without the interruptions and risks associated with real systems, offering valuable insights

into operational performance and improvement feasibility [2].

FlexSim is a discrete-event simulation software designed for modeling, analyzing, and optimizing processes across various sectors, enabling a graphical representation of operational flows and the testing of different scenarios. The Experimenter, an integrated tool within FlexSim, allows for the automated execution of multiple simulations with varying parameters, enabling comparative analyses and the identification of the most efficient configurations [3]. This combination facilitates the evaluation of alternatives prior to practical implementation, reducing operational costs and risks.

FlexSim stands out among simulation software for offering advanced functionalities for scenario modeling and performance analysis. It enables detailed mapping of workflow and cycle times, and, with Experimenter, facilitates sensitivity analyses and parameter tuning, providing a comprehensive view of potential improvements. In logistics centers, simulation is essential for managing systems with multiple variables and high complexity, enabling cost reductions and improved customer responsiveness [4].

Growing competitiveness also requires logistics centers to find ways to boost productivity and

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reduce waste [5]. The application of methodologies such as Lean has shown positive results, enabling the reduction of unnecessary movements and layout optimization [6]. These methods are even more effective when integrated with simplified computational modeling techniques, allowing for quicker and more efficient process analysis. This combination not only enhances performance but also supports faster decision-making, contributing to a more dynamic and responsive operational environment [7].

In this context, this article aims to conduct a systematic literature review on the use of FlexSim and Experimenter in optimizing manual parcel handling cells, focusing on productivity improvement scenarios. By analyzing multiple case studies and technical papers, the study seeks to synthesize evidence on the effectiveness of these tools in improving logistics flows and eliminating bottlenecks, contributing to the advancement of optimization practices in parcel handling centers.

Furthermore, the current evolution towards Logistics 4.0, characterized by the integration of advanced digital technologies, highlights the importance of simulation tools in strategic planning. FlexSim and Experimenter, when used in combination, not only enable virtual testing of operational strategies but also align with broader industry trends, such as predictive analytics, real-time monitoring, and data-driven decision-making.

Materials and Methods

This study follows an initial approach based on PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) criteria as the foundation for the systematic review. The choice of PRISMA is justified by its ability to provide a structured guide for identifying, selecting, evaluating, and synthesizing studies. This methodology is widely used across research areas due to its effectiveness in ensuring rigor and transparency for the validity of the findings.

In this work, adopting some PRISMA criteria allowed the systematic organization of information

and the identification of consistent patterns across different studies. This was necessary given the analysis of multiple variables across scenarios related to modeling and simulating logistics processes.

During the selection process, it was observed that the number of studies focusing specifically on the optimization of manual parcel handling cells was limited. Studies applying FlexSim in logistics centers, focusing on productivity enhancement and idle time reduction, were considered. Studies without quantitative results or those applying simulation tools outside logistics contexts were excluded.

Data was collected from academic databases such as ScienceDirect and Google Scholar, as well as from university repositories and logistics/operations management conferences. The search included terms like “Parcel handling”, “FlexSim”, “Center logistics”, “Simulation optimization”, “Experimenter”, “Layout optimization”, and “Lean Manufacturing”.

Following PRISMA guidelines, the review followed four main phases: identification, screening, eligibility, and inclusion [8-9]. Searches were conducted in Scopus, Web of Science, and ScienceDirect using descriptors such as “discrete event simulation”, “parcel center”, “manual operations”, and “FlexSim”. A total of 138 records were initially identified, from which 32 duplicates were removed. After title and abstract screening, 76 articles were excluded for not fitting the thematic scope. Thirty studies were fully assessed, with 18 excluded due to lack of relevant data or for not addressing manual logistics contexts. Thus, 12 studies formed the final analysis base.

Effect measures were fundamental to assess the operational efficiency of the simulated scenarios. The effect measures included: percentage increase in productivity (based on processing capacity) and reduction in idle time. This approach allows identifying which changes generate the most positive impact, highlighting the importance of testing multiple configurations prior to implementation.

Variables such as performance increase, waste reduction, operator travel distance and machine utilization rate were analyzed. Specific FlexSim and Experimenter variables were also considered, such as the number of iterations required for optimization and the configuration time for experiments. These items were selected to ensure consistent comparisons across studies.

To synthesize results, some studies were compared using performance tables. The synthesis method followed a qualitative meta-analysis approach, identifying common optimization patterns and improvements. Qualitative analysis was used to assess variable impacts across various logistics scenarios.

Following systematic review methods, a qualitative analysis was performed to identify patterns and discrepancies in simulation practices across studies. This method is consistent with similar reviews in logistics, particularly regarding logistics flow optimization using computer simulation.

Results and Discussion

The reviewed studies present a wide variety of logistics scenarios, ranging from fragile product distribution center operations to layout planning for workflow optimization. This diversity reflects the inherent complexity of logistics processes and the need to customize solutions according to each system's demands.

The analyzed variables are highly specific to the context of each study. For instance, while some emphasize worker utilization rate as a key indicator for manual processes [4], others highlight the importance of reducing operator travel distances in picking scenarios [10].

When analyzing the studies in a cross-comparative manner, it becomes evident that performance gains are often interdependent across metrics. This relationship suggests that layout optimization and workflow redesign, which directly impact operator movement, may serve as a primary driver for improvements in other performance indicators.

This specificity shows that although simulation with FlexSim and Experimenter tool are broadly applicable, result interpretation strongly depends on the logistics context. Therefore, it is essential to acknowledge that metrics from different studies are not directly comparable without considering their operational settings.

Another relevant aspect identified is the replicability of improvements across different logistics contexts. Even though each study had unique operational characteristics, certain strategies proved beneficial in multiple environments. While simulation outputs must be validated for each specific case, there is a repertoire of best practices that can serve as a starting point for optimization projects.

The studies analyzed in this review offer relevant insights for improving manual parcel handling processes, especially when using FlexSim and Experimenter for logistics optimization. The comparison of performance indicators extracted from the selected studies is summarized in Table 1.

An important valuable finding relates to process movements and productivity improvement in picking. This study emphasizes the importance of mapping each step and using simulation to test scenarios that eliminate low-value activities [10].

Simulation enables precise control over material flows and better resource allocation, key benefits for logistics projects. Examples show that integrating tracking technologies with simulation can offer a comprehensive, detailed view, enabling real-time adjustments to layouts and operational routines.

The study demonstrated that it is possible to maximize the performance of a manual parcel handling cell by focusing on layout redesign and workflow configuration based on simulation. This is crucial, as even small changes can substantially impact capacity and productivity.

The Experimenter tool proved essential for testing scenarios, measuring performance, and optimizing processes, as simulation provides a practical way to visualize the effects of such changes [3]. This learning reinforces the importance of

Table 1. Summary of performance indicators in reviewed studies.

Title	Performance increase (%)	Machine utilization (%)	Operator distance reduction (%)	Travel time reduction (%)	Daily turnover increase (%)
Application of FlexSim in Handling Fragile and Unmachinable Items in a Logistics Center [1]	35	-	-	-	-
Resource Optimization via Discrete Event Simulation [2]	-	86.84	-	-	-
A Flexsim-based Optimization for the Operation Process of Cold-Chain Logistics Distribution Centre [4]	-	-	-	-	87
Lean Methodologies in a Distribution Center [6]	-	-	81.9	82	-
Development of a Continuous Improvement Program at the Logistics Center [10]	-	-	19	24	-

analyzing each process phase carefully to identify and reduce redundant activities, improving flow, response times, and removing non-value-added activities.

It was also observed that integrating simulation with emerging technologies can bring additional benefits, such as real-time process analysis and detailed resource availability and optimization [11]. These technologies include the Internet of Things (IoT), enabling remote monitoring and control of logistics equipment, and AI algorithms for demand forecasting and optimized resource allocation, which can significantly enhance operational performance.

This insight suggests that combining simulation with innovative technologies could be a future goal for this research, optimizing operator tracking and reducing process cycle time.

This learning process can guide continuous improvement practices, with simulation functioning not only as an analysis tool but also as a safe and economical experimentation mechanism.

The review also offers practical insights, such as the need for ongoing revision of simulation

scenarios, as changes in operational parameters directly impact performance [12]. This continuous adaptation ensures that the simulation remains aligned with real conditions, maximizing its effectiveness as a decision-making tool.

Conclusion

The systematic review demonstrates that FlexSim and Experimenter can be powerful tools for optimizing operations in manual parcel handling centers. The analysis revealed that simulation not only facilitates testing of layout and resource allocation configurations but also offers valuable insights into process adjustments in response to demand variations and operational bottlenecks. The observed patterns, such as the effectiveness of Lean methodologies in reducing waste and optimizing processes, show that simulation can also be integrated with emerging technologies to maximize operational efficiency.

Although simulations using FlexSim and Experimenter are effective, it is important to recognize the limitations in generalizing results.

Studies based solely on data from specific companies or logistics centers may not fully reflect other operational realities. Therefore, future studies should consider diverse operational contexts to enhance the external validity of their findings.

Additionally, future work should explore integrating FlexSim simulations with IoT systems, artificial intelligence algorithms, and predictive analytics in real-world scenarios. Including these elements could highlight the benefits of technological integration, contributing to innovation in logistics centers.

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A Review of Computational Vision applied to Materials Selection

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This bibliographic review shows the increasing number of works in the field of computational vision applied to materials selection within the framework yolo. The results obtained with the search present studies from the years of 2021 to 2025, published in the platforms Dimensions, Google Scholar and Web of Science. It was observed that studies in that field are increasing, have increased from 2023. Researches in that field indicate that solutions for defects, classification and material properties are the most common fields of study. Architectures of Deep Learning and Convolutional Neural Networks are the most common used techniques, together with framework Yolo for integration in already built-in solutions

Keywords: Material Selection. Material Identification. Artificial Intelligence. Computer Vision. Yolo.

Currently the development of intelligent systems tends to use the generation of images and Artificial Intelligence (AI) elements of machine vision and computer vision [1] to raise the relevance in the field, since the task uses a lot of computer resources and needs a lot of data. That technology has been applied in material selection field, for example, recycling, for classification and sorting waste [2]. Other solutions consist of analyzing materials properties, using scanning electron microscopy (SEM) analysis, to identify microstructure degradation [3], but most of the solutions used currently are related to material sorting, another related area is the solid waste identification, with Machine Learning (ML) algorithms that can identify metals, non-metals and plastic [5]. A tool identified in that bibliographic research for materials selection using AI is the YOLO framework, for its practicality and an already built-in interface for system integration and ease of use [2,5,6]. It has a CNN architecture build in its structure, and make easier for defining and changing hyperparameters, besides it has a wide benchmark of increased performance and resource usage. YOLO is an open source tool which enables

its use and improvement by the community, It has an advantage of using pre-trained models and databases for an existing weight-model creation, which improves the accuracy of new models [6]. Models are influenced by the environment of the scene, when light is stronger or darker, some characteristics may be affected, dropping accuracy [7,8], depending on the model architecture and tools used to create it, for that frameworks like YOLO within built in models are used for a wide range of applications strengthening their accuracy [9].

Yolo framework uses, Deep Learning (DL) architectures, that are suitable and used for crack detection in roads, as an example of applicable solution in traffic policies outperforming traditional techniques [10], and Convolutional Neural Networks (CNN) architectures that are derived from DL. CNNs are used for segmentation tasks and more detailed information from images.

Another field of study and application are the automotive industry, being enhanced by YOLO's, techniques like data augmentation, and the use of CNN layer architectures are capable of identifying car damage better [11]. Another classification solution with the current methods are identifying variances in the same material, as plastic for example, it has transparent plastic, which is a hard task for humans, together with some systems it can complete those tasks [2].

Computational Vision can be integrated with robot systems, either for helping human tasks, or

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to improve them. Waste collection is a delicate activity, with challenges within sorting objects, not only from inorganic but from organic source [4,12]. Health and Industry activities in that field may affect people constantly, for that solutions using AI with object detection and segmentation are applied, together with frameworks like YOLO [13].

In that context this work has the objective of searching studies in the field of AI and materials selection.

Materials and Methods

This literature review has the objective to summarize the fields of Computer Vision applied to the materials selection, with the most recent and discussed techniques and approaches. Therefore the research was done using scientific platforms like “Google Scholar”, “Dimensions” and “Web of Science” in the period of 2021 - 2025.

The research was made in the month of July of 2025, it involved a careful keyword search to cover the main interest areas, the words were combined using boolean operators (AND, OR) to maximize the scope and the results

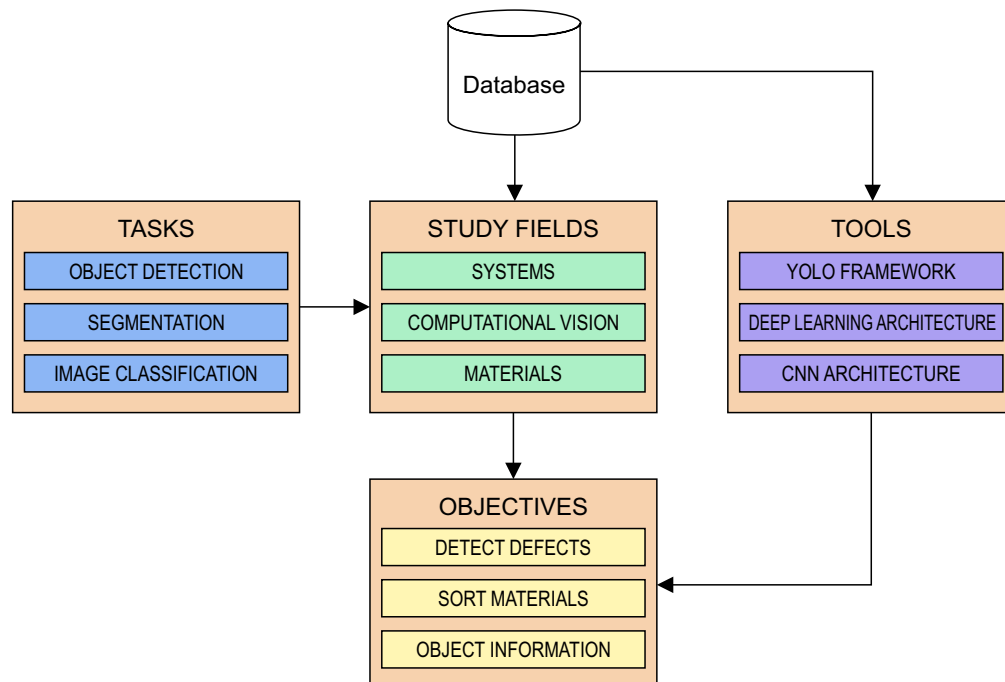
relevance. The specific key-words combination was (“Material selection” OR “Material identification”) AND (“Artificial intelligence” OR “Computer vision”) AND “yolo” .

Results and Discussion

The results observed in the search appoint that there are many useful cases for applying object detection in current solutions, the most common cases are referred to identify materials patterns in 2D images [14], within the help of Deep Learning and Convolutional Neural Network techniques. There are many researches in quality control of materials, as defects are subject of many studies and are hard to detect [15].

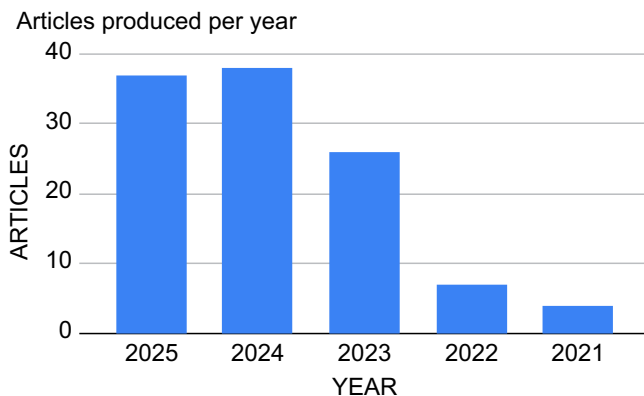
The works and solutions available follow a pattern shown in Figure 1, most common tasks are Object Detection, Segmentation and Image Classification [2,4,5,15]. Many of the works in the field have a challenge of using specific database for their needs, also there are ways of maximizing the efficiency of already existing tools [16], for instance in inspection systems, with the aid of CNN techniques.

Figure 1. Standard workflow of computational vision solutions and the tools used.



The search using keywords and their combinations resulted in a total of 146 publications. The quantitative of the studies is presented in Figure 2, showing an increase from 2023 indicating an interest of the subject and its use.

Figure 2. Summary of the articles found researching through platforms, Dimensions, Google Academic, Web of Science.



The papers have results for the current “state of the art” reference, using CNN techniques together with YOLO and integration with other systems as robots, the accuracy in models generated by that architecture have higher results, even when under light different conditions [2]. Another approach used by the papers, is the improvement of existing models and architectures, in recent studies using data from cameras and millimeter-wave radar to have an intersection between the layers of information and bounding boxes, had great results, showing that it is possible to generate solutions based on image conditions difficulties, since it affects deeply the results [7].

Object detection is a common task in industry and services, there was a proposal of solutions where a specific type of material shall be identified and sorted in waste management. A great result was classifying materials in metals, non-metals and plastic, in the paper, with that the algorithm scope is reduced, further increasing its accuracy with CNN architectures in the model [4], besides that using pre-trained models with labeled images from the materials type that should be identified, proved to be very useful.

In real case-scenarios like waste management, materials and objects can be in the same layer, and probably will not be separated without being covered by other objects. Training techniques for grouping more than one object with same characteristics in a layer and then detecting its label proved efficient, as well as training multi label detection in images with objects separated [4].

Identifying material properties have also been subject of current studies, in Review of Pavement Defect Detection Methods [15], some techniques were stated, and most of them are currently being used in general solutions. Crack Detection Based on Binary Classification, where an image is divided into sub-images and then the probability of a property (crack, defect), can be measured on the number of labeled “defect blocks” [15], and Crack Detection Based on Multi-Class Classification, for deciding which type of “defect” the image has, in a multi label problem, in that case the image is classified if it has cracks or not, if it has then a grid label is created using principal component analysis vector to decide the direction type [15]. Crack Detection Based on Pixel Segmentation is another approach where pixels are labeled or scored due to its properties. Crack Detection Based on Object Detection is the technique in which a bounding box is used to determine the object edges, in three steps, first extracting image features, second propose candidate regions for objects and finally classification the objects bounding boxes regions. Most of the results and comparisons in the study between the datasets using the techniques showed a result above 85%, they use architecture models of CNN [15].

Conclusion

The works from the search show that solutions used in the materials field are related to object segmentation, object detection and image classification, most of them are related to sortage of materials and identifying materials property, either for defects or quality control quantification.

Deep Learning and Convolutional Neural Networks are the architecture approaches used for modeling Computational Vision Solutions. They have better accuracy and response to modeling creation than other techniques.

YOLO is a well known and solution integrated framework used in most cases. It enables the creation of faster and resource optimized models that can be used in many different cases and scenarios.

Acknowledgement

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Bibliographic Analysis of Compressive Sealants for Metal Supported Solid Oxide Fuel Cells and Electrolyzers

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Metal-supported solid oxide fuel cells (MS-SOFCs) and solid oxide electrolysis cells (SOECs) stand out for high power density, fuel flexibility, and long-term stability. Their durability relies on compressive sealants that prevent gas crossover and maintain integrity under high temperatures. Mica- and vermiculite-based gaskets are widely used for compliance, easy assembly, and hermeticity without high-temperature processing. This work reviews compressive sealant materials, configurations, and hybrid strategies for MS-SOFC and SOECs. Emphasis is placed on the structural, thermal, and chemical behavior of phlogopite papers and Thermiculite® gaskets, which show superior stability, low porosity, and reduced leakage, especially with glass-ceramic layers. Hybrid approaches, such as transient liquid-phase bonding, are also considered for lowering operating temperatures while preserving strength. Finally, the availability of Brazilian phlogopite and vermiculite is highlighted as an opportunity for cost-effective, locally sourced sealants.

Keywords: Compressive Sealants. MetalSupported SOFC. Vermiculite. Mica Paper. Thermiculite®.

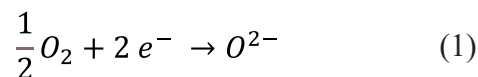
Abbreviations: MSSOFC, MetalSupported Solid Oxide Fuel Cell. SOFC, Solid Oxide Fuel Cell. CEV, Chemically Exfoliated Vermiculite. ECS, Electrochemical Society.

With the continuous growth of global energy demand, the search for cleaner and more sustainable methods of electricity generation has intensified [1]. In this context, hydrogenbased technologies such as fuel cells have gained prominence by combining low environmental impact with a high degree of technological maturity [2].

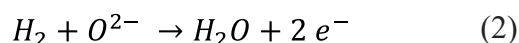
Among the various types, metalsupported solid oxide fuel cells (MSSOFCs) stand out for operating at high efficiency levels, surpassing the thermodynamic limitations imposed by the Carnot cycle on conventional heat engines [3]. The operating principle of SOFCs involves the reduction of oxygen at the cathode to produce O^{2-} ions, which migrate through a ceramic electrolyte to the anode. There, they react with hydrogen to form water vapor and release electrons. These electrons travel through an external circuit, generating electric current, and return to the cathode to complete the electrochemical cycle

[2], as illustrated in Figure 1 and described on Equations 1 and 2 [2].

Equation 1. Oxygen reduction at the cathode



Equation 2. Hydrogen oxidation at the anode

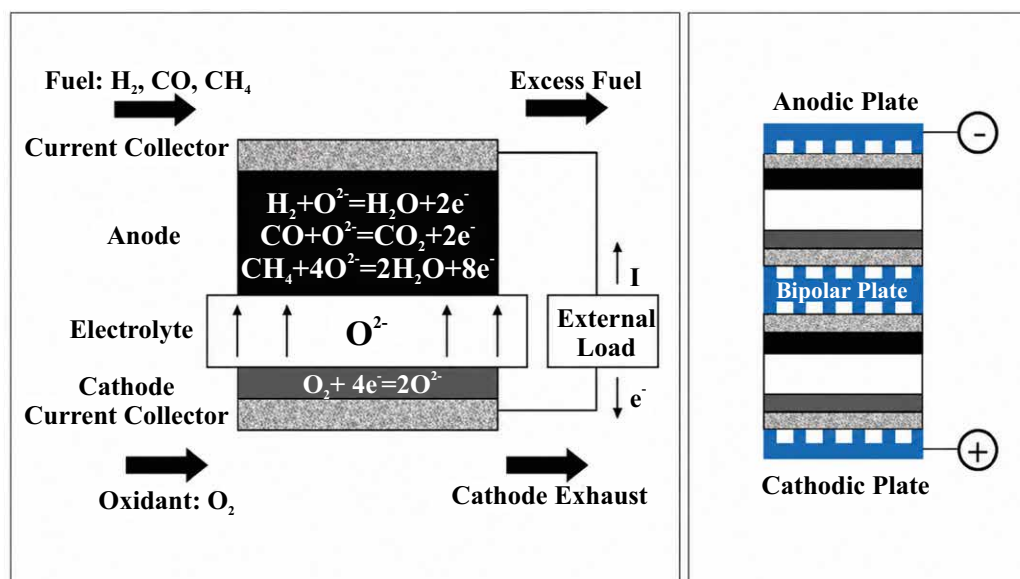


AMS-SOFC comprises five primary components: the metal support, the anode, the electrolyte, the cathode, and the sealant. The metal support, often made from oxidation-resistant ferritic stainless steels such as Crofer 22 H, provides mechanical strength, electrical conductivity, and thermal stability at high operating temperatures [4]. The anode is typically a Ni-YSZ (yttria-stabilized zirconia) cermet, which offers high electronic conductivity and catalytic activity for hydrogen oxidation [5]. The electrolyte, commonly YSZ, ensures high O^{2-} ionic conductivity within the operating temperature range and acts as a gas-tight barrier between electrodes [5]. The cathode is often composed of perovskite oxides such as LSCF ($La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-\delta}$), applied by techniques like plasma spray to maximize oxygen-reduction reaction rates [6].

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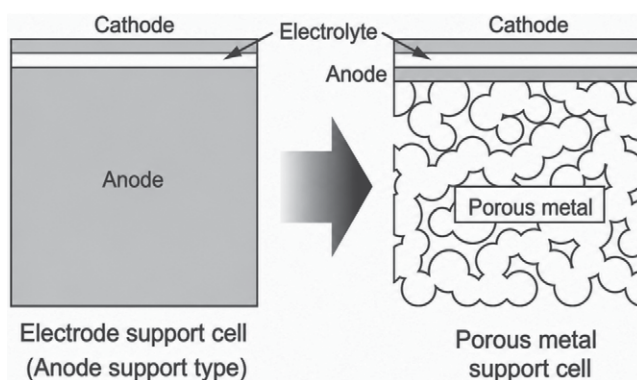
Figure 1. Schematic of the metal-supported solid oxide fuel cell operating principle.

Source: Fallah Vostakola, and Amini Horri [1].

Sealing these components into a hermetic stack is crucial for maintaining efficiency and long-term durability under continuous operation. Sealants for SOFCs are classified into three main families: rigid (glass-ceramic-based), compressive (mica- or vermiculite-based), and compliant (braze-based) [7]. Among these, compressive sealants have drawn significant attention due to their excellent leak-tightness and ease of assembly [7]. Techniques such as Ni–Sn transient liquid-phase bonding using Crofer 22 H interconnects have been explored to create low-temperature metal seals, highlighting the versatility of combining metallic and compressive methodologies for enhanced sealing performance [4].

Despite these advances in materials and cell architecture, one of the main technological bottlenecks for commercial deployment of SOFCs is the sealing of the system [7]. The high operating temperatures (700–1000 °C) and the porous nature of many components, as shown in Figure 2, pose serious challenges to achieving a durable, hermetic, and reliable seal [3].

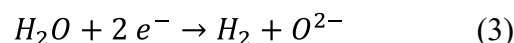
Solid Oxide Electrolysis Cells (SOECs) operate on principles similar to those of SOFCs but in reverse, using electrical energy to drive the electrochemical splitting of steam (and sometimes

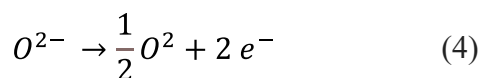
Figure 2. Key components of a metal-supported solid oxide fuel cell stack.

Source: Tucker [3]

CO₂) into hydrogen and oxygen at elevated temperatures. In an SOEC, steam is introduced at the cathode, where it receives electrons to form hydrogen gas and oxygen ions (O²⁻). These oxygen ions migrate through a dense ceramic electrolyte to the anode, where they release electrons and form O₂ gas. This reaction is described by Equations 3 and 4.

Equation 3. Hydrogen reduction at the cathode



Equation 2. Oxygen oxidation at the anode

The high operating temperatures (700–900 °C) of SOECs improve thermodynamic efficiency and enable the co-electrolysis of H₂O and CO₂ to produce syngas (H₂ + CO), a valuable feedstock for synthetic fuels. However, this high-temperature environment imposes stringent requirements on all cell components, particularly the sealants, which must maintain hermeticity and chemical stability over prolonged operation in dual atmospheres (reducing on the cathode side and oxidizing on the anode side).

Glass-ceramic sealants were investigated specifically for SOEC applications and highlighted that maintaining compatibility between the thermal expansion coefficients (CTEs) of the sealant and adjoining components is essential to avoid mechanical failures during thermal cycling [8]. It was proposed a BaO–SiO₂-based composition with optimized CTE and good long-term adhesion in H₂/H₂O atmospheres, maintaining structural integrity after 2000 h of exposure at operating conditions without delamination or gas leakage [8].

Further developments introduced SrO-containing glass-ceramics tailored for SOEC use [9]. These sealants exhibited high electrical resistivity (>10⁵ Ω·cm), stable sealing behavior under simulated electrolysis conditions, and appropriate softening temperatures (T_g and T_fs) for stack assembly and operation [9]. The composition designated HJ14 showed promising results due to its thermal stability and mechanical robustness, indicating its potential as a candidate for long-duration SOEC operation [9].

These findings underscore the critical role of tailored sealant design for the durability and efficiency of SOECs, especially under the combined challenges of high temperature, differential pressure, and dual-gas atmospheres.

Choosing a suitable sealant is crucial not only for structural integrity but also for maintaining

cell efficiency and longterm durability under continuous operation.

The main sealant families for SOFCs and SOECs can be divided into three groups: rigid (glassceramicbased), compressive (mica or vermiculitebased), and compliant (brazebased). Among these, the compressive sealants have attracted attention for their excellent leaktightness and ease of use [2].

In Bahia, the occurrence of phlogopite—a rock used to produce phlogopite mica—in the Carnaíba district of Pindobaçu has been widely investigated by CETEM as a potassium source and as a promising raw material for micabased compressive sealants [10]. Moreover, the municipality of Brumado hosts vermiculite and talc mining concessions operated by companies such as Mineração Urimamã, evidencing local deposits of this key vermiculite for compressive sealants [11]. With significant reserves also in states like Goiás and Piauí, Brazil holds strategic potential to become a major national producer of mica and vermiculite compressive sealants, meeting sealing demands in SOFCs and other highperformance industrial applications [12].

In this scenario, the present article aims to perform a comparative analysis of the main compressive sealants applied in solid oxide fuel cells and electrolyzers.

Materials and Methods

A bibliographic review was performed using the Scopus database and the Bibliometrix software.

The keywords “Sealing” and “SOFC” were used to identify articles containing both terms in the title, abstract, or keywords, yielding 465 papers.

The number of citations per article was then analyzed, revealing that the mostcited paper was published in 2009; hence, a filter was applied to include only articles published from that year onward, resulting in 348 documents.

Graphs illustrating the bibliographic dynamics of the topic were generated with Bibliometrix, as shown in Figure 3.

Results and Discussion

Based on the bibliographic review, it was possible to understand the sealing process using compressive sealants and their physical properties. These sealants consist of mineral flakes (mica or vermiculite) bound together with an organic or inorganic binder, forming a sheetlike material [13], as shown in Figure 4.

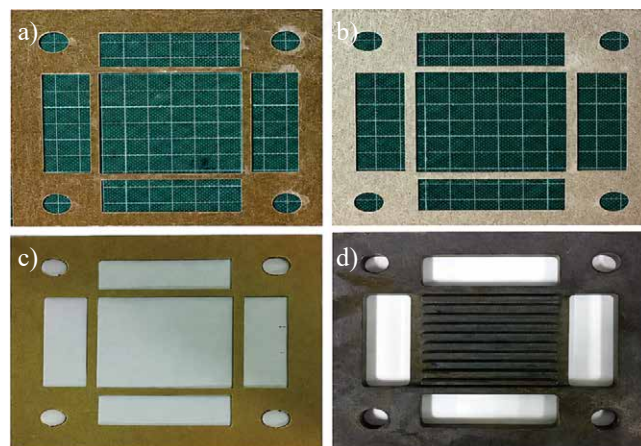
During sealing, the gasket material is subjected to a compressive force, either via springs or bolts through the stack structure [14]. Under compression, the mineral flakes rearrange, and at high temperatures they retain this compressed arrangement, preventing gas leakage.

The main compressive sealants can be divided into two subgroups: micabased sealants and vermiculitebased sealants (Thermiculite®) [13].

Mica-Based Sealants

Micabased sealants are composites made by incorporating mica flakes into a cellulose pulp, which is then formed into sheets through a process analogous to paper making [15]. This yields a material with excellent electrical insulation

Figure 4. Photographic comparison of compressive sealant materials.

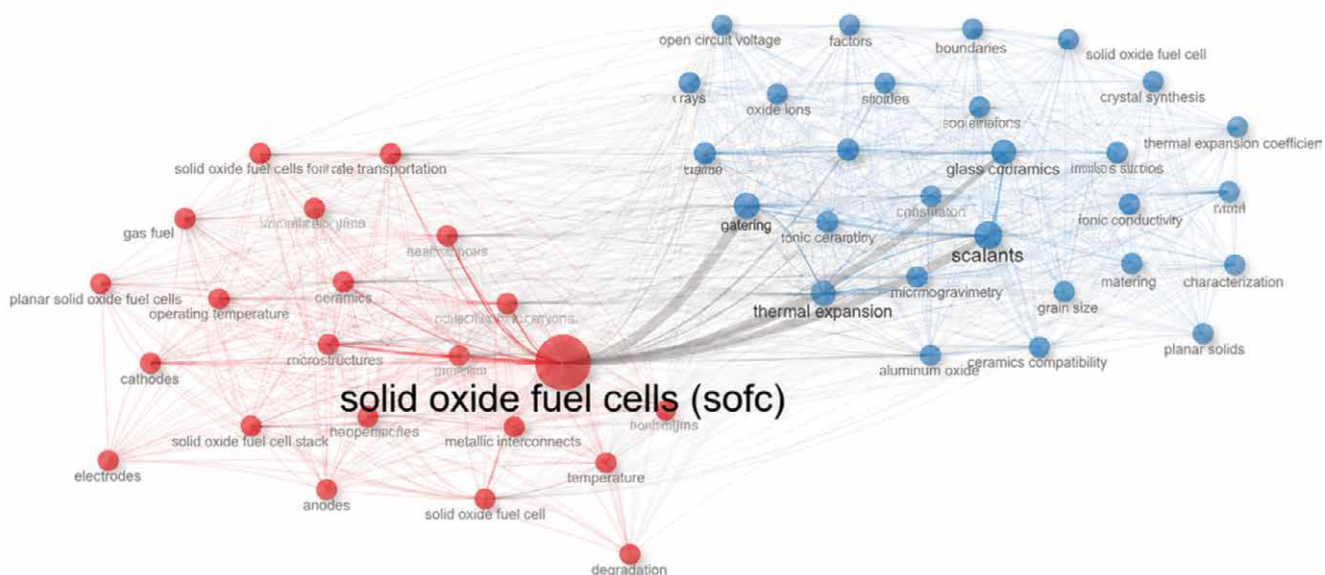


a) mica paper, b) flexible mica paper, c) thermiculite 866, and d) the interconnector.

Source: Nguyen and colleagues [5].

properties. However, the presence of organic binders can lead to material degradation during SOFC thermal cycling [13]. In comparative leakrate tests, mica paper sealants exhibited higher leakage rates than vermiculitebased sealants at both room temperature and at 800 °C

Figure 3. Bibliometric analysis of SOFC sealing literature.



Source: Made by the authors

[5]. Expansion tests also showed that mica paper undergoes significantly greater thickness increase upon heating, indicating higher final porosity under operating conditions [5].

Thermiculite® (Vermiculite-Based)

Thermiculite® is a sealing material manufactured from vermiculite, a phyllosilicate mineral similar to mica [13]. Specifically, Thermiculite® 866 consists of chemically exfoliated vermiculite (CEV) and steatite, with no organic binders, thereby avoiding degradation during fuel cell operation [13].

To further enhance performance, Thermiculite® 866 LS was developed by applying a glassy sealant layer to the contact surfaces of the material, enabling effective sealing at lower compressive pressures, as shown in Figure 5 [13].

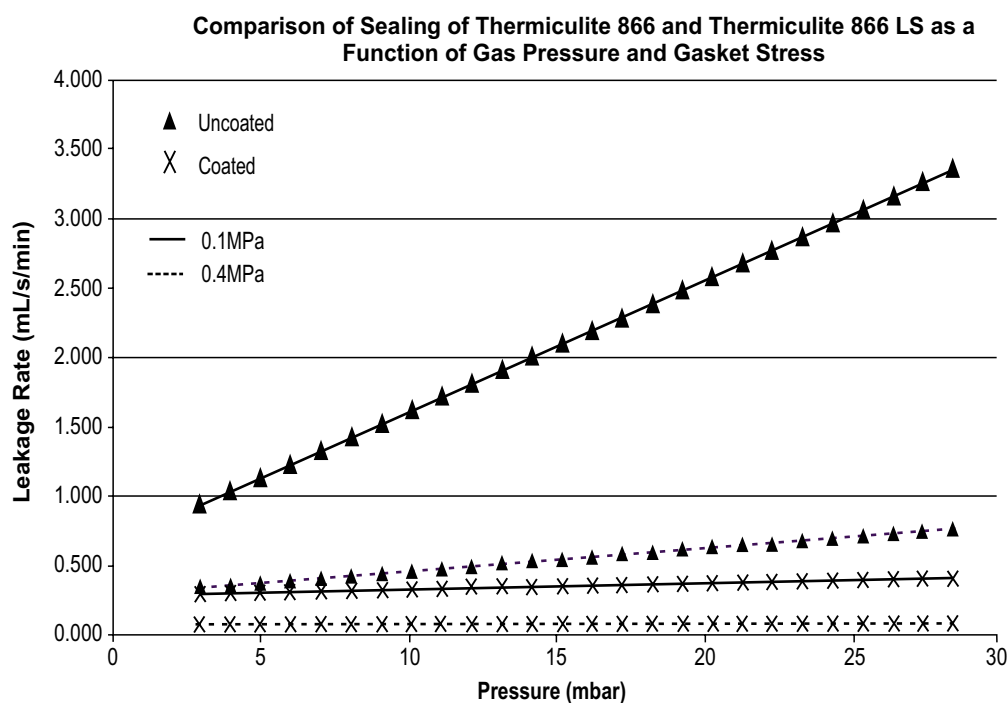
Studies on Thermiculite® CL87 and CL87 LS models indicate that material compressibility significantly decreases by 200 °C, suggesting that initial compression should be performed at room temperature before the first heatup cycle [15].

Comparison

When comparing micabased and vermiculitebased (Thermiculite®) compressive sealants, critical differences emerge. Thermiculite® demonstrates superior dimensional stability, with only 0.068 mm thickness change after 100 hours at high temperature, whereas mica paper and flexible mica paper expand by 0.51 mm and 0.48 mm, respectively [16]. This lower expansion in Thermiculite® corresponds to lower final porosity and improved leak tightness, as confirmed by lower leakrate measurements under identical hydrogen flow and temperature conditions (Figure 6) [5].

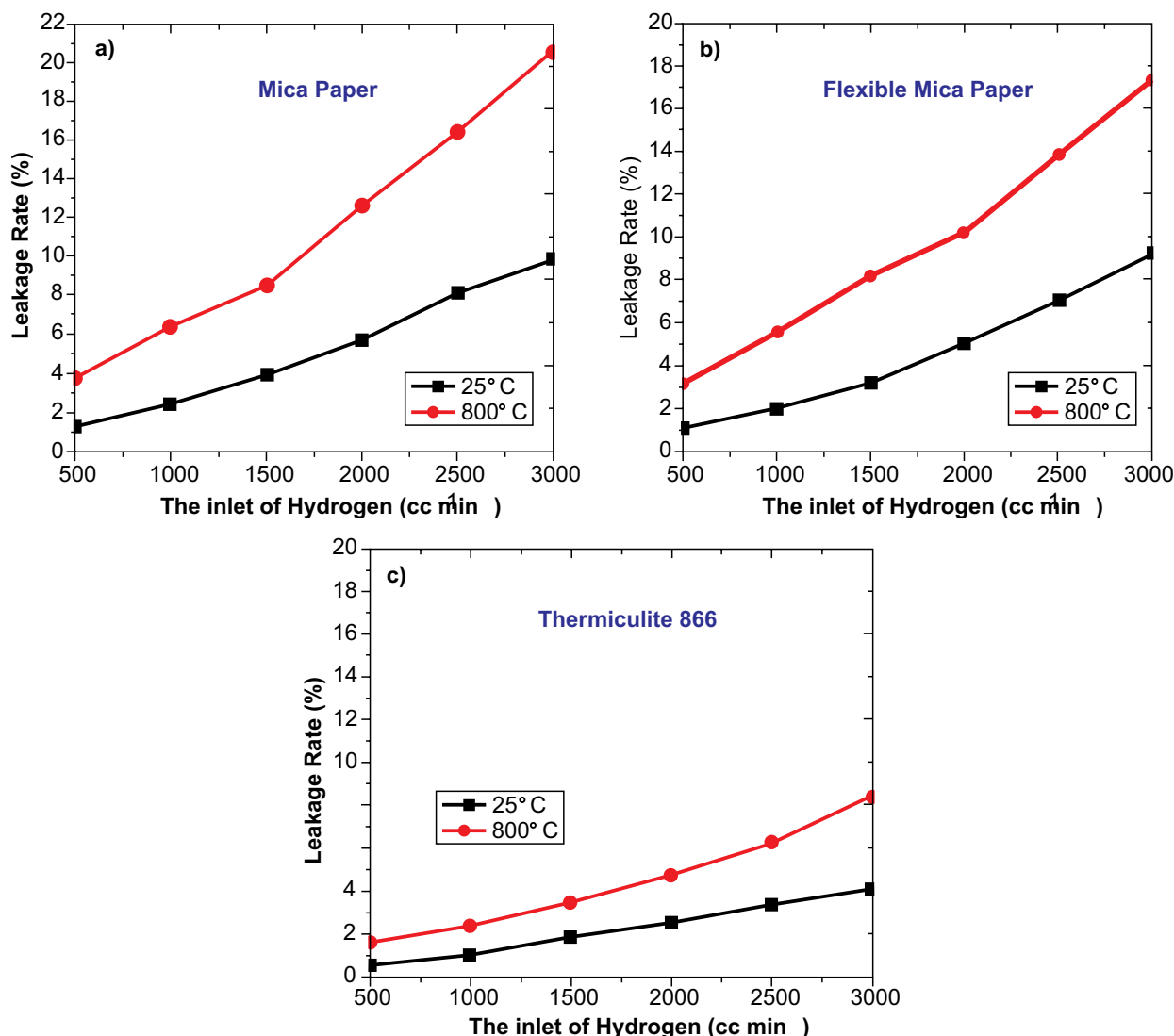
Comparative life-cycle assessments have shown that vermiculite-based sealants have a lower environmental footprint, considering raw material extraction and end-of-life recyclability, compared to synthetic polymer-based gasket alternatives [17]. Preliminary evaluations suggest that leveraging domestic vermiculite resources could offer cost benefits over some imported sealant materials, potentially supporting the economic viability of large-scale SOFC implementation.

Figure 5. Sealing performance: Thermiculite® 866 vs. 866 LS under varying conditions.



Source: Hoyes, and Rautanen [13].

Figure 6. Leakage rate comparison of mica- and vermiculite-based sealants. Rate of leakage through the sealants: a) mica paper, b) flexible mica paper, and c) thermiculite 866.



Source: Nguyen and colleagues [5].

Practically, Thermiculite® also requires a lower compressive force to achieve adequate sealing compared to Mica [13]. A hybrid approach—combining compressive and rigid sealant features—has emerged as promising. Coating Thermiculite® with a glassceramic layer (e.g., 866 LS and CL87 LS) drastically reduces leakage and enhances resistance to internal pressure variations, merging the mechanical resilience of compressive sealants with the low permeability of glasses, while requiring less compressive load [13].

Conclusion

The comparative analysis of mica and vermiculitebased compressive sealants reveals the clear superiority of Thermiculite® for SOFC and SOEC applications. Its higher dimensional stability at elevated temperatures, lower porosity, and consequently lower leak rates make it a more reliable and efficient option. Additionally, the ability to achieve hermetic sealing at reduced compressive forces—especially in glasscoated

versions like Thermiculite® 866 LS—offers significant advantages for stack structural integrity and longevity. The advancement toward hybrid sealant solutions, combining the best traits of compressive and rigid materials, represents a promising pathway to overcome sealing challenges in SOFCs and SOECs, supporting the commercial viability of this clean energy technology.

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Energetic Use of Biomethane in Brazil

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Biomethane is a renewable energy source with great strategic potential for Brazil's energy transition, especially due to its compatibility with the natural gas infrastructure. Produced through anaerobic digestion of organic residues, biogas mainly contains methane (CH₄) and carbon dioxide (CO₂). After purification, the resulting biomethane reaches a methane concentration of 90–98%, making it suitable for injection into gas distribution networks or use in transportation, industry, and residential sectors. This study aims to analyze the potential, challenges, and opportunities of biomethane in Brazil, considering its contribution to the decarbonization of the energy matrix and the sustainable use of organic waste. The research adopts an exploratory and descriptive approach, based on a bibliographic and documentary review of scientific publications, institutional reports, and updated sectoral data. The results indicate that biomethane, in addition to reducing dependence on fossil fuels, contributes to waste management and the generation of carbon credits. As an advance over the current state of the art, this study systematizes recent data on production, public policies, and practical applications of biomethane in Brazil, highlighting its growing role in the national energy transition.

Keywords: Biomethane. Energy Transition. Renewable Fuel. Greenhouse Gas Emissions. Organic Waste Valorization.

The growing reliance on fossil fuels has been a major driver of greenhouse gas (GHG) emissions, intensifying the urgency for energy alternatives that are both sustainable and scalable. Among the viable solutions for decarbonizing the energy sector, biomethane stands out as a strategic renewable fuel that can support a gradual and effective transition toward a low-carbon energy matrix. While it is currently unfeasible to completely and immediately eliminate combustion-based energy sources [1], biomethane offers a practical bridge by directly substituting fossil natural gas (NG) without requiring significant changes to existing infrastructure.

Driven by mounting pressure for environmental policies and the rising global energy demand, there is a strong incentive to develop cleaner,

renewable fuel technologies [2]. In this context, scientific research, industrial innovation, and societal awareness have increasingly converged around the development of technologies that not only reduce emissions but also create value from organic residues. Among these, gaseous biofuels—particularly biomethane—have gained attention for their ability to transform waste into energy, leveraging resources such as agricultural by-products and solid or liquid urban waste to power cities, industries, and transport systems.

Biogas, the precursor of biomethane, is produced through the anaerobic digestion of organic matter, and consists mainly of methane (CH₄) [~60%] and carbon dioxide (CO₂) [~35%], along with trace gases like nitrogen, ammonia, hydrogen sulfide, and carbon monoxide [3–5]. Its exact composition depends on the type of substrate, the digestion technology used, and process conditions. After purification to remove impurities and non-combustible gases, biogas is upgraded to biomethane, achieving a methane concentration of 90–98% [7,8], as shown in Table 1. With superior calorific value and combustion characteristics, biomethane matches or even

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exceeds the quality of fossil NG, qualifying it as a fully renewable replacement, often referred to as Renewable Natural Gas (RNG) [9,10].

According to the *Panorama of Biogas in Brazil* [8], the country's theoretical biogas potential reaches 85 billion m³/year—enough to replace approximately 70% of its diesel demand and 40% of its electricity needs. These figures reveal a massive untapped opportunity.

Biomethane presents Brazil with a unique chance to integrate a renewable, decentralized, and low-emission fuel into its energy matrix. Its versatility, compatibility with existing NG infrastructure, and ability to valorize organic waste make it not only a clean energy source but also a driver of circular economy, rural development, and climate mitigation. Investing in biomethane today means advancing toward a cleaner, more resilient, and energy-sovereign tomorrow.

Materials and Methods

The methodology adopted in this work was exploratory and descriptive research, based on bibliographic and documentary research, with indirect data collection from official agencies and public and private institutions. It also considered scientific literature, technical production, sector

reports, and legal and technical standards related to biomethane in Brazil. The collected data were analyzed qualitatively and quantitatively, with the deductive method being the central vector for conducting the work. The analysis of the collected data allowed us to describe the characteristics of the biomethane sector in Brazil.

Energy Overview of Brazil

The analysis of the National Energy Balance 2025 [6] shows that combustion is responsible for 81% of the country's Internal Energy Supply (OIE) (Table 2).

BEN 2025 also shows that the transportation and industry sectors consume 65% of the energy produced in the country (Table 3).

An analysis of the energy consumption structure in the industrial sector indicates that combustion supplies 80% of the energy consumed by industry, and electricity only 20%. In the transportation sector, combustion accounts for 99% of the energy consumed by industry, and electricity contributes 1% [6].

Biomethane Production in Brazil

The country's biomethane production capacity is 667,000 m³/day (Table 4).

Table 1. Composition range of combustible gas mixtures.

Compounds	Concentration (Volume %)		
	NG	Biogas	Biomethane
Methane (CH ₄)	91	50-70	90-98
Carbon Dioxide (CO ₂)	0,61	25-40	0
Hydrogen Sulfide (H ₂ S)	< 0,001	0,5-1	0
Nitrogen (N ₂)	0,32	< 0,001	0
Ammonia (NH ₃)	< 0,001	< 0,01	0
Carbon Monoxide (CO)	0	< 0,01	0
Calorific Value [MJ/ Nm ³]	27	20–25	35–39
Directly replaces NG?	-	No	Yes

Source: Prepared based on Coelho and Colleagues [5] and Empresa de Pesquisa Energética [6].

Table 2. Breakdown of internal energy supply-OIE.

SOURCES	[%]
Combustion - Oil and Derivatives	34
Combustion - Sugarcane Biomass	17
Combustion - Natural Gas	10
Combustion - Firewood and Charcoal	8
Combustion - Black Liquor and Other Renewables	8
Combustion of Mineral Coal	4
Hydraulic Power	12
Wind Power	3
Solar Power	2
Uranium	1
Other Non-Renewables	1
Total	100

Source: Prepared based on data from EPE [6].

Table 3. Breakdown of internal energy supply by sector (%).

Sector	[%]
Transportation	33
Industrial	32
Residential	11
Energy	9
Non-Energetic use	6
Agriculture	5
Services	4
Total	100

Source: Prepared by the Authors based on data from [6].

Energetic Use of Biomethane

Biomethane can be used in the same applications as natural gas (NG), meaning it is a natural and

Table 4. Companies authorized to sell biomethane / ANP.

TOTAL	Production Capacity By Raw Material			
	MSW	ASP	SUGARCANE	TOTAL
Nm ³ /d)	433	230	4	667

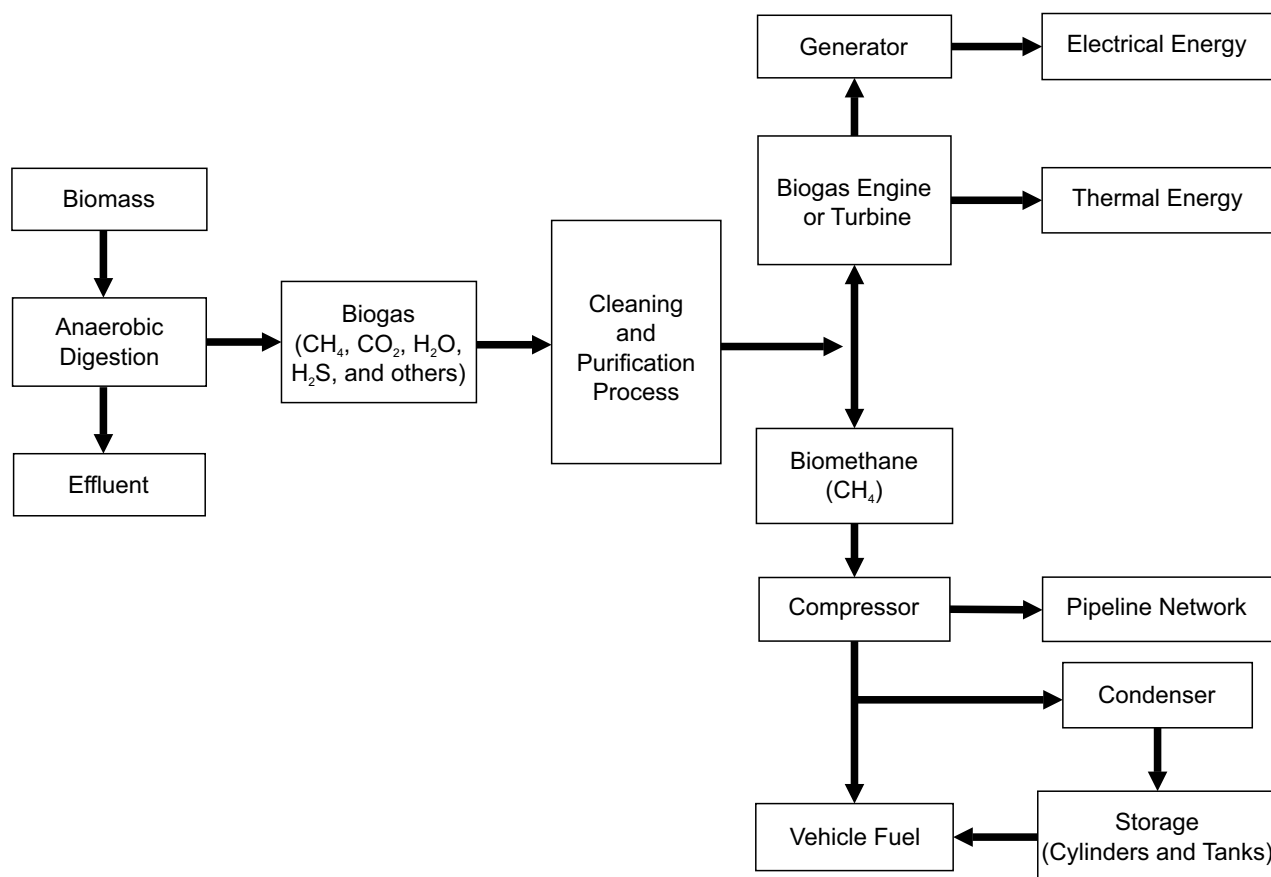
Source: Prepared by the authors based on data from the ANP's Biomethane Producers Dynamic Panel [11].

Legend: MSW = Urban Solid Waste Deposited in Sanitary Landfills; ASP = Agroforestry and Commercial Organic Products and Waste; SUGARCANE = Vinasse and Sugar and Ethanol Production Waste.

direct substitute for fossil natural gas (NG), but with renewable sources (NGR). However, its production for use as a NG substitute requires biogas purification, a process that reduces the concentrations of moisture, CO₂, and other lower concentrations, resulting in a methane-rich gas (biomethane) with similar physical and chemical properties to natural gas. After compression, biomethane can be used directly in the pipeline for supply in various applications, including vehicles. After compression, condensation, and storage in tanks or cylinders, it can also be used in various applications, including vehicles (Figure 5).

The transportation sector is the largest CO₂ emitter in Brazil, according to the BEN 2025 (Table 5), which causes environmental problems that can be reduced with the use of alternative energy sources such as biomethane.

For vehicle use, adjustments may be necessary due to methane's high octane rating, but the biggest problem is its energy density, much lower than that of diesel [19]. This requires tanks that can withstand the operating pressure and offer satisfactory range. Furthermore, biomethane functions as a vehicle fuel in the same way as natural gas (or fossil methane) and, therefore, can be used in conventional natural gas (NGV) vehicles. Different types of biomethane engines can be used: A specific biomethane gas engine - operates on 100% biomethane; a gasoline/biomethane flex-fuel engine; a diesel/biomethane flex-fuel engine; and a tri-fuel engine - a combination of a flex-

Figure 5. Simplified flowchart of the production and end use of biogas and biomethane.**Table 5.** Total emissions (2023) in Mt CO₂-eq.

Sectors	Mt CO ₂ -eq	%
Transportation	214	50%
Industry	75	17%
Residences	19	4%
Other Sectors	124	29%
Total	431	100%

Source: Prepared by the Authors based on data from the BEN 2025 – Summary Report [6].

fuel vehicle with a natural gas (NGV) vehicle. A flex-fuel vehicle uses gasoline and ethanol, either exclusively or as a blend. Thus, a tri-fuel vehicle runs on gasoline, ethanol (or both), and natural gas or biomethane. Perhaps it is the most appropriate choice for Brazil, which has had a consolidated and efficient fuel ethanol program for 50 years.

Advantages of Using Biomethane

The Gross Calorific Value (GCV) of biomethane ranges from [9.47 to 11.94] kWh/m³ [12] and is equivalent to the GCV of natural gas. In energy terms, 1 Nm³ of biomethane is equivalent to 0.87 liters of diesel [8].

The use of biomethane as a renewable fuel helps mitigate GHG emissions, and its production from organic waste prevents the release of methane into the atmosphere [13] and uses urban solid waste and agro-industrial byproducts for energy. Through anaerobic digestion, this waste is converted into biogas, which, after purification, results in biomethane. This process not only reduces the amount of waste sent to landfills but also generates biofertilizer as a byproduct, contributing to soil fertility and closing the nutrient cycle.

Opportunities for Biomethane Growth in Brazil

Brazil has vast potential to expand biomethane production, especially by integrating new economic sectors and exploring different biomass sources.

Sugarcane Sector

The sugarcane industry presents significant opportunities for biomethane production. Waste such as filter cake and vinasse can be used to generate biogas, which, after purification, results in biomethane. Studies indicate that, by 2034, it is possible to produce approximately 3.3 billion Nm³ of biomethane from this waste, meeting approximately 39% of the agricultural sector's diesel demand [14].

Urban Solid Waste (MSW) Sector

Municipal waste management represents another frontier for the expansion of biomethane. The anaerobic decomposition of organic waste in landfills and sewage treatment plants generates biogas, which can be converted into biomethane.

The waste sector is responsible for the emission of 3.17 Mt of methane [15], and biomethane production can address emissions from the waste sector in Brazil if it uses municipal solid waste (MSW), domestic and industrial liquid effluents, and agricultural waste as raw materials. With the New Regulatory Framework for Basic Sanitation, established by Law 14,026 of July 15, 2020, which reinforces the National Solid Waste Policy, an increase in waste collection and treatment is expected, expanding the potential for biomethane production in this sector [16].

Animal Protein Sector

Brazil is one of the world's largest producers of animal protein, generating large volumes of organic waste. This waste, from slaughterhouses and farms, can be used to produce biogas and,

consequently, biomethane. The use of this waste contributes to the sustainability of the sector and the diversification of the energy matrix [7].

Carbon Credit Generation in Biomethane Production

Biomethane production involves the capture and purification of biogas resulting from the anaerobic decomposition of organic waste, a process that prevents methane emissions into the atmosphere, allowing the generation of carbon credits. For each ton of CO₂ equivalent not emitted, it is possible to generate a biofuel decarbonization credit (CBIO), a tradeable security on the stock exchange. According to the National Biofuels Policy (RenovaBio), established by Law 13,576/2017 [17], which established a carbon credit program linked to the fuel distribution sector, biomethane regulation is considered one of the eligible routes for generating decarbonization credits (CBIO) under ANP Resolution 758/2018 [18]. Integrating biomethane production into carbon credit generation mechanisms represents an effective strategy for promoting environmental and economic sustainability in Brazil. With appropriate public policies and investments in infrastructure and technology, the country can establish itself as a leader in the production of renewable biofuels and in mitigating climate change.

Conclusion

Biomethane represents a key opportunity for Brazil to accelerate its transition toward a low-carbon, diversified, and circular energy matrix. As a renewable fuel with physical-chemical properties and calorific value comparable to those of fossil natural gas, biomethane can be seamlessly integrated into the existing gas infrastructure, avoiding the need for costly system adaptations. Its production from organic residues—agricultural, industrial, and urban—transforms environmental liabilities into strategic energy assets.

The environmental benefits of biomethane are particularly significant: it reduces methane

emissions from waste, mitigates overall greenhouse gas (GHG) emissions, and contributes to achieving international climate targets. Moreover, its production process generates valuable co-products such as biofertilizers and green CO₂, supporting the circular economy and sustainable agricultural practices.

Economically, biomethane offers new revenue streams through the generation of decarbonization credits (CBIOs), in line with Brazil's RenovaBio program. This not only improves its financial viability but also attracts investments in renewable energy and infrastructure, especially in rural areas where feedstock availability is high.

Technologically, biomethane enables energy decentralization and strengthens energy security by providing a reliable, renewable, and local energy source. Its use in transportation—especially in heavy-duty vehicles—can significantly reduce Brazil's oil dependency and pollution in urban centers.

In summary, biomethane is not just a fuel—it is a catalyst for innovation, environmental restoration, and sustainable development. Its large-scale adoption offers Brazil a rare convergence of environmental responsibility, energy resilience, and economic opportunity. By embracing biomethane, Brazil positions itself as a global leader in renewable gas and paves the way for a just and efficient energy transition.

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Optimization of Water Supply in Smart Cities: An Integrated Approach to Data Management, Artificial Intelligence, and Smart Water Technologies

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Abstract: Amid growing water scarcity and losses in distribution networks, it is crucial to find effective solutions that increase efficiency and ensure the sustainability of water management. This global demand is reflected in the regional scenario of the state of Bahia, especially in the capital, Salvador. Data from the Bahia State Basic Sanitation Regulatory Agency (AGERSA) points to recurring problems with water interruptions that are not sufficiently unpredictable. Based on this issue, this article presents a literature review on emerging technologies to improve water supply management in smart cities, with specific application to the capital of Bahia. The methodology employed involves a technical review of the main technologies currently applied in Smart Water Networks, including smart meters and advanced sensors for water quality monitoring, proposing an integrated model based on the Internet of Things (IoT) and Big Data analysis (AI; Machine Learning). The expected results include improved operational efficiency, greater accuracy in early detection and response to critical events such as leaks and supply interruptions, as well as greater transparency of water supply and treatment information for users and managers. The conclusion is that the implementation of the solution will significantly contribute to the technical, operational, and environmental sustainability of urban water systems.

Keywords: Smart Water. Artificial Intelligence. Internet of Things. Data Management. Smart Cities.

Water management is facing a scenario of increasing complexity, marked by a growing global water scarcity and continuously rising consumption. It's estimated that the world will face a 40% water deficit by 2030 [1], a situation that climate change is expected to worsen. A substantial part of this challenge lies in the significant losses in obsolete water distribution systems, where the average waste in Europe reaches 26% and, in some regions, can exceed 50% [2]. In Brazil, this percentage is 37.8%, but states such as Acre and Amapá exceed 60% [3]. In Salvador, approximately 57% of drinking water is lost before reaching consumers [4].

Data from the Basic Sanitation Regulatory Agency of the State of Bahia (AGERSA) reveal that water supply management faces significant challenges. In 2023, Salvador accounted for 37.74% of all complaints received by the AGERSA ombudsman's office across the state,

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with water scarcity alone accounting for 35.47% of these complaints [5]. Frequently associated with unpredictable and irregular supply interruptions by the Baiana Water and Sanitation Company (Embasa), these complaints signal not only a direct impact on citizens' quality of life but also substantial difficulties for the planning and regulatory efficiency of public services. Thus, innovative technological solutions, such as integrated smart systems based on IoT and predictive data analysis, are emerging as promising alternatives to optimize management, anticipate interruptions, improve transparency, and support both consumers and the agencies responsible for providing and supervising these services.

In addition to waste, the existing, often aging, water infrastructure presents critical operational challenges. Problems like leaks, meter failures, water theft, and contamination are recurring, directly impacting the efficiency of the supply and the quality of the water provided [6]. The lack of real-time monitoring and analysis in this infrastructure worsens the situation, making the identification and correction of anomalies a slow and costly process. Complementing these issues is

the pressing matter of non-revenue water, which refers to water that is produced and introduced into the distribution system but does not generate revenue for sanitation companies [6-8]. This loss, directly linked to leaks, theft, and faulty meters, has a significant financial impact, drastically reducing the revenues of water utilities.

In response to growing urban challenges, smart cities are emerging as a development paradigm, using advanced technologies to improve the management of infrastructure and urban services [9-11]. At the heart of this concept is the application of big data, vast quantities of information generated by sensors, devices, and human interactions which, when properly analyzed, offer profound insights into urban systems [9-11]. This real-time monitoring capability allows cities to optimize the efficiency, sustainability, and resilience of their infrastructures, anticipating future demands and ensuring the allocation of resources according to current and future needs.

Against this backdrop of challenges and technological advances, this article aims to conduct a literature review on water supply system optimization, focusing on the integration and synergy between advanced data management technologies, Artificial Intelligence, and Smart Water. The analysis of these concepts sought to explore how their combination can revolutionize urban water systems, enabling more accurate monitoring, proactive anomaly detection, and more strategic and efficient decision-making.

Materials and Methods

This section details the methodological approach used for the systematic literature review, aiming to identify, analyze, and synthesize the most relevant information on optimizing water supply in smart cities through the integration of data management, Artificial Intelligence, and smart water technologies.

The literature search was conducted in renowned academic databases, including Scopus, Web of Science, and IEEE Xplore. The search strategy

involved combining key terms related to the main concepts of the article. The terms were grouped and combined using Boolean operators (“AND,” “OR”) to maximize the scope and relevance of the results.

Identifying the central themes of this review allowed for the best combination of terms. The keywords and Boolean operators used were (“Smart Water Technologies” OR “Smart Water”) AND “Smart Cities” AND (“Data Management” OR “Big Data” OR “Data Analytics”) AND (“Artificial Intelligence”). The publication period of the documents was limited to 2014 to the present to cover the recent years relevant to the popularization of the concepts evaluated. A descriptive analysis of the literature revealed that most of the studies are very recent (from 2020 to 2025), demonstrating the topic’s relevance and relevance.

The article selection process followed the steps of searching, using the aforementioned strategy; selecting, through a preliminary reading of titles and abstracts, and then reading in full, those articles most closely related to the topic; and finally, a qualitative analysis of eligible articles: peer-reviewed articles addressing the optimization of water supply in urban environments, smart cities, or water systems, and discussing the application of data management (including Big Data), Artificial Intelligence (including Machine Learning), and/or smart water technologies (such as IoT, sensors, and smart meters).

Thematic Analysis

In response to these water management challenges, the water sector is evolving toward a more sophisticated paradigm characterized by the integration of physical, cyber, and human components, giving rise to Cyber-Physical-Human Systems (CPHSs) [7], [12-13]

Cyber-Physical-Human Systems (CPHSs) in Water

The evolution of sanitation companies to CPHSs represents a fundamental shift in how

water services are managed and delivered. In these systems, there is a growing interconnectedness and interdependence between physical assets, such as pumps, pipes, and valves, and cyber systems, which encompass software, data, the Internet of Things (IoT), and Artificial Intelligence (AI) [14]. Human-social interactions, involving employees, customers, and the community, are equally crucial as they influence and are influenced by these components [12]. This integration aims to optimize demand management, improve customer service, and enhance contamination detection, among other operational and strategic benefits.

Improved water demand management is driven by the collection of real-time consumption data through smart meters and IoT sensors, overcoming the limitations of mechanical meters that require manual reading and offer low data resolution [15]. This data granularity and temporality allow for a deep understanding of water usage patterns, helping utilities to optimize distribution, predict demand peaks, and implement more effective demand management strategies. Furthermore, customer service is enhanced with the availability of transparent information and the ability to make payments and report problems online [12]. Machine Learning (ML) and AI algorithms can analyze large volumes of data to identify abnormal patterns, such as leaks and unusual consumption, with high accuracy, even in low-resolution data [16].

There are several examples of this approach being applied in the water sector by cities, companies, and governments. In leak detection and prevention, the city of Oslo, for example, monitors more than 1,550 km of water pipes to obtain real-time information and reduce leaks [12]. Similarly, in Melbourne, Australia, Southeast Water, Yarra Valley Water, and City West Water collaborated on a digital metering program that saved more than 40,000 liters of water per day through leak detection and correction, in addition to identifying the loss of 50,000 liters per day on customer properties [12]. The Mackay Regional Council in Queensland, using AMI (Advanced Metering Infrastructure) technology, issued approximately 400 leak

notifications per month, saving approximately 834 ml of water [14]. In water quality, Veolia developed the “waternamics” platform, which, when applied to the drinking water network in Lyon, France, helped identify emerging chemical substances in the Rhône River [12].

Despite the benefits, the complexity and emerging risks of interconnectedness in CPHSs are notable. A limited understanding of these interdependencies can result in wasted resources, service interruptions, systemic failures, and a compromised customer experience [8], [12]. Specific challenges include the integration of existing IT systems, which are difficult to integrate with newer systems and incur high maintenance costs. The aging infrastructure, with many pipes at the end of their useful life (averaging 50 years, but many at 70-100 years), increases the propensity for leaks and ruptures [16]. Environmental sustainability is a concern, given the impact of climate change on rainfall patterns and water quality, in addition to the energy costs of data processing. Data management presents challenges of volume, velocity, and variety, as well as security and privacy issues. A lack of cybersecurity and data analysis expertise and skills in the workforce, as well as customer and community engagement, are additional barriers to technological adoption [12].

Theories of Smart Cities, Sustainability, and Urban Resilience

The theories of Smart Cities, Sustainability, and Urban Resilience converge to provide a fundamental conceptual framework for optimizing water supply in the contemporary scenario. At its core, the Smart City Theory conceives of urban environments that use the integration of Information and Communication Technologies (ICT) to enhance urban services and infrastructure [12]. AI and big data are essential components of this vision, maximizing resources and increasing sustainability [17]. In this context, water utilities are transformed into “digital utilities,” employing smart meters, sensors, and analytical platforms to manage the water cycle more efficiently.

The Theory of Sustainability, in turn, emphasizes the need to meet the demands of the present without compromising the ability of future generations to meet their own needs. Predictive analysis allows for optimizing resource use, minimizing water waste, and reducing the carbon emissions associated with treatment and distribution, contributing to a smaller urban environmental footprint [18]. The ability to predict water demand and detect leaks in real time, for example, ensures that water is used more consciously and efficiently. Although AI is not a universal solution for all sustainability problems, its value lies in its ability to facilitate improved environmental governance and promote resource conservation [18].

Finally, the Theory of Urban Resilience focuses on the ability of cities to resist, absorb, and recover from shocks and stresses, such as natural disasters, infrastructure failures, or supply interruptions [19]. The integration of ICT and big data strengthens this resilience, optimizing environmental management and risk mitigation. Real-time monitoring of water infrastructure allows for the proactive detection of anomalies, such as pressure variations or contamination, enabling rapid responses and minimizing the impact of disruptive events [19]. Predictive analysis, powered by AI, can anticipate floods, droughts, or demand peaks, empowering cities to dynamically adapt their systems and ensure the continuity of essential services.

Current Challenges and Barriers

Despite the promising benefits, the digital transformation in the water sector faces significant challenges and barriers that need to be addressed to ensure a successful and sustainable implementation of Smart Water systems. One of the main obstacles is the integration of legacy IT systems and aging infrastructure [12,20-21].

Many sanitation companies still depend on outdated software and hardware, which are expensive to maintain and difficult to integrate with new technologies. This reliance on old systems hinders the full adoption of Industry 4.0

technologies, making modernization a complex and costly process. The physical infrastructure, with pipes that are decades old, requires high investments for modernization, which exacerbates the challenges of technological updates.

Data security and privacy in IoT networks and critical systems constitute another crucial barrier. The growing interconnectedness of IoT devices in water systems increases the likelihood of cyberattacks, with documented incidents already resulting in sewage leaks and water contamination [21-22]. The privacy of consumer data is an ethical concern, as detailed information about water consumption can reveal personal lifestyle patterns and behaviors, such as times of home occupancy, meal schedules, and even religious habits. Ensuring data sovereignty and compliance with data protection regulations, which vary between countries, is fundamental to building user trust and preventing the misuse of sensitive information.

The lack of standardization and interoperability among technologies is a persistent problem that prevents the mass adoption of Smart Water solutions. The diversity of IoT technologies and protocols makes it difficult to integrate heterogeneous systems, resulting in “excessive pilots” instead of widespread adoption. The absence of clear interfaces and standardized implementation guidelines for smart water solutions creates barriers to scalability and interoperability between platforms and devices.

Data quality and methodological gaps in CPHS representation also pose significant challenges. The vast amount of big data generated can be inconsistent, incomplete, or in varied formats, making analysis and the extraction of actionable insights difficult [12]. The lack of logical approaches to optimize data value and the absence of long-term strategic planning for technology adoption and data management are important methodological gaps. Additionally, there is a lack of methods to identify, categorize, and prioritize evolving risks, as well as to model the emergent behavior of CPHSs, which are complex systems with

dynamic and unpredictable interactions. A limited understanding of increasing interconnections can lead to unintended consequences and the ineffectiveness of interventions.

Research Direction

To overcome current challenges and maximize the potential of water supply optimization in smart cities, several research directions are essential, focusing on enhancing the synergy between data, AI, and Smart Water.

The development of new models for consumer behavior and anomaly detection is fundamental. Research can delve into the application of advanced Machine Learning and Deep Learning techniques to improve the accuracy of identifying abnormal consumption patterns, such as leaks and unauthorized water use. It is crucial to develop models that effectively handle low-resolution and inconsistent data, a common reality in legacy systems. The ability to proactively identify the intent of fraud or the causes of anomalies, such as faulty meters or tampering, can optimize field inspections and reduce non-revenue water losses.

Advances in sensor and communication technologies are continuous and critical. Research should focus on developing next-generation sensors that offer greater accuracy, reliability, and resilience, with capabilities for monitoring network management and operational parameters such as flow, pressure, consumption, and water level; and quality parameters such as pH, turbidity, total dissolved solids, dissolved oxygen, residual chlorine, and biological parameters. The improvement of Low Power Wide Area Network (LPWAN) technologies, such as LoRaWAN, SigFox, and NB-IoT, is vital to ensure long-range, low-energy connectivity in massive IoT deployments in urban and rural environments [22-23]. The ability to deal with interference and optimize spectrum allocation in massive IoT scenarios should also be a priority.

Finally, the development of governance frameworks for CPHSs and AI is essential. As

technology is not neutral and can reconfigure social relationships and values, it is crucial for future research to address how AI and CPHS systems can be governed responsibly and ethically. Research should also explore how changes in human relationships, roles, and processes within organizations are renegotiated by the adoption of smart technologies, and how interdisciplinarity can support the understanding and management of these complexities.

Conclusion

The optimization of water supply in smart cities, through the synergy between Artificial Intelligence and data management in Smart Water systems, is emerging as an indispensable strategy to face global water challenges. This article explored the transformative potential of this approach, detailing how the evolution toward Cyber-Physical-Human Systems (CPHSs) and the integration of advanced technologies can revolutionize water management. The references addressed demonstrate that digitalization allows for real-time monitoring, the precise detection of anomalies such as leaks and contamination, and the implementation of predictive maintenance strategies, resulting in water savings, reduced operational costs, and improved service quality.

The fundamental contribution of this study lies in the synthesis of knowledge that highlights the importance of a more comprehensive and multidisciplinary approach. Integrating social and ecosystem dimensions into the design and governance of CPHSs is crucial, given that this technology can reconfigure access to water. Smart meters, for example, can help identify losses and manage consumption, but if implemented unevenly, they can marginalize low-income communities that cannot afford them or lack access to monitoring devices. Proper governance would ensure that all citizens have equitable access to the technology and its benefits.

Water system optimization must go beyond reducing financial losses. Governance must ensure

that AI and data management systems also work to protect water ecosystems, reduce pollution, and ensure long-term sustainability.

Recommendations for future actions involve the development of robust policies that encourage technological adoption and the ethical use of AI, the training of the workforce to deal with new digital demands, and the promotion of close collaboration among all stakeholders—governments, utilities, the private sector, academia, and civil society. By addressing these challenges in an integrated and proactive manner, the potential of AI and data management in Smart Water can be fully realized, contributing significantly to the water security and sustainability of global cities.

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