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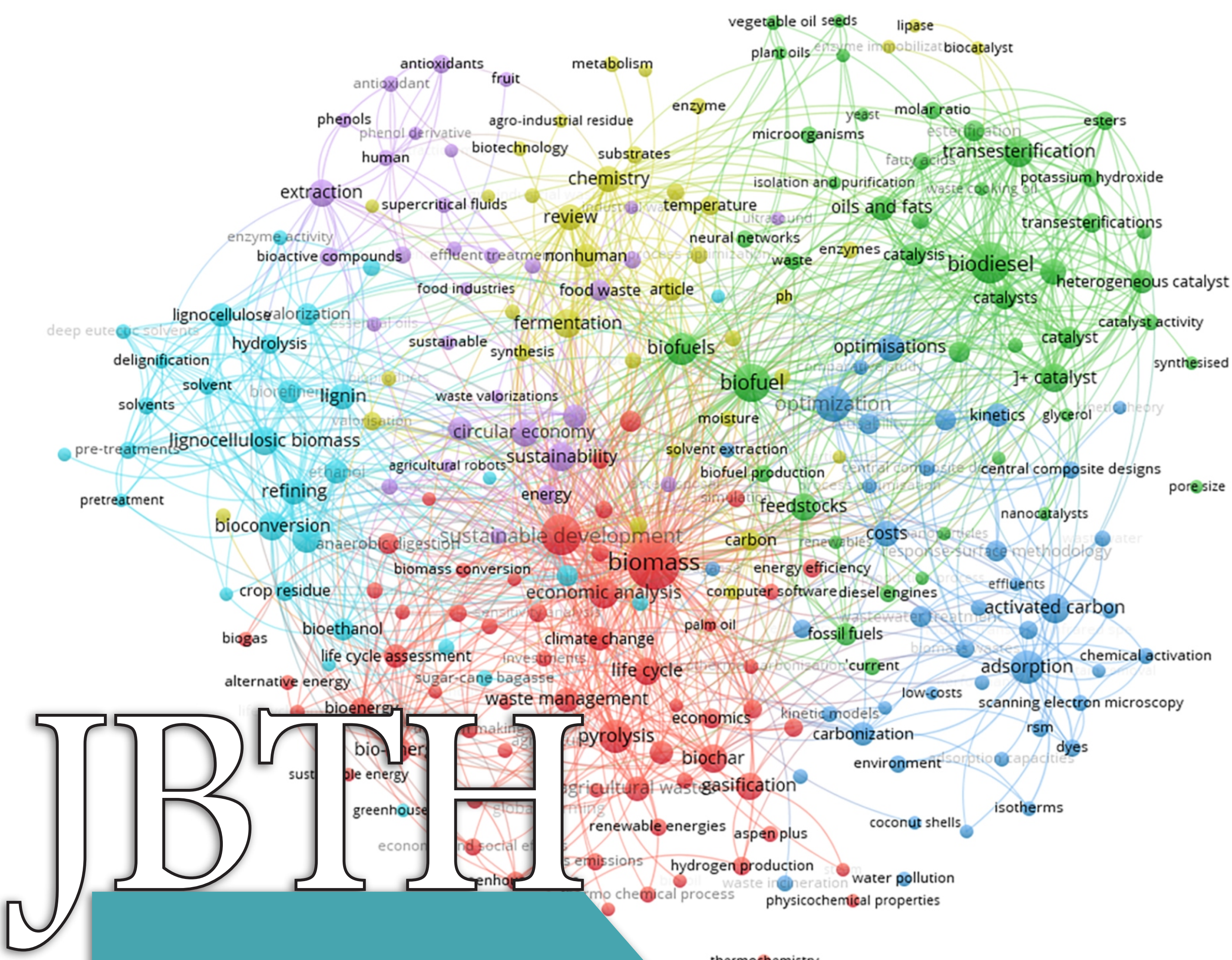

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Volume 9 • Number 6 **SUMMARY** *June 2026*

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COVER: Figure 10. Keyword co ocurrence analysis in clusters through network visualization in VOSviewer® (Search 5). Biorefinery of Cocoa Waste: A Systematic Review and Bibliometric Analysis by Yan Valdez Santos Rodrigues et al. J Bioeng. Tech. Health 2026;9(6):601.

Modeling and Simulation of a Bacteriological Incubator

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Bacteriological incubator consists of equipment that provides an optimized environment for the development of bacteria, frequently used for the development and testing of antibiotics and antiseptics. This work aims to perform white box modeling and simulation of a bacteriological incubator with an operating range of up to 50 °C, presenting a comparison of the P (Proportional), PI (Proportional-Integral) and PD (Proportional-Derivative) compensators in the process loop, enunciating the advantages and disadvantages. Furthermore, the simulation was developed in the MATLAB/Simulink environment, using as reference the commercial bacteriological incubator BF115, manufactured by BINDER. As a result, for the heating process, the PI compensator meets the design requirements and it was verified in computer simulation, while the others, even for cooling, do not meet these requirements and they are not implementable.
Keywords: Bacteriological Incubator. Modelling. Compensation. Simulink. Temperature.

Bacteriological incubators consist of equipment that provides an optimized environment for the development of bacteria, through the monitoring and compensation of thermal variables, such as temperature and humidity [1]. This equipment is often at microbiology laboratories for cultivation of pathogenic bacteria, antibiotics research, clinical diagnosis, and antiseptic efficiency testing.

Typically, the air in the bacteriological incubator has a reference temperature of 37 ºC (degrees Celsius), which is the average temperature of human body, so it reaches the carbon dioxide levels necessary to promote maintenance of cell growth. For the system design of a bacteriological incubator, the microorganisms require a particular set of parameters, such as temperature and humidity, for their growth and development [2].

As work references, Abo Al-kibash and Dana [2] made a similar proposal but focusing on prototyping and experimental results. On the other hand, Pugachuk, Burkhanova and Fominykh [3] contributed to expressing the temperature variation inside one bacteriological incubator. Zermani and Mami [4] proposed a theoretical modeling for incubator systems, but for another application scenario, to reduce heat loss by evaporation.

Thus, based on literature and similar works' research, if the process' variables have not been monitored and compensated correctly, then this equipment as a product will not guarantee an optimized environment for bacterial cultures. In this context, the paper aims to develop a mathematical model of a bacteriological incubator system, to understand the process dynamic behavior for monitoring and compensating the average internal temperature.

This document has been segmented into the following content: section 2 – methodology – about the system plant, actuator and compensators' modeling, section 3 – results – about the simulation of the process, section 4 – conclusion – and references.

Materials and Methods

To model the process of a bacteriological incubator system, this work assumes a Proof of Concept (PoC) with one temperature sensor, two temperature actuators – one for heating and another for cooling – and cubic geometry for the plant – with side L – to promote the same geometry on front, side and superior view (Figure 1).

The graphical representation adopted to model the bacteriological incubator system is shown in Figure 2. The system input-output relationship is the

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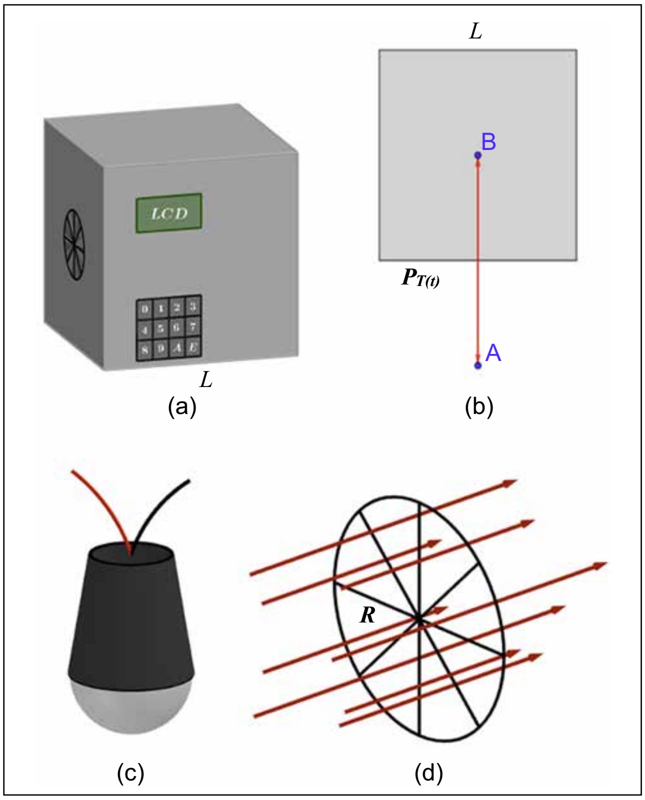
Figure 1. PoC bacteriological incubator system.



user's desired temperature and the average internal temperature measured.

In this system, it absorbs thermal energy and dissipates it to the environment using actuators that amplify or attenuate the average internal temperature, operating one at a time through a switching system.

PoC Creation Steps

The steps used to develop the PoC is shown in Figure 3.

Thermal Process Modeling

For simplicity, the PoC is considered a linear time-invariant (LTI) system, and the system identification method based on white box model is applied to obtain the process transfer function using the Laplace transform [5].

Typically, the thermal processes exhibit one thermal resistance (R) and one thermal capacitance (C), being analogous to modeling an RC series electrical circuit [6]. This type of modeling helps extract system performance specifications for control, such as the time constant.

The principle of calorimetry indicates the law of conservation energy in thermal systems, i.e., the variation in thermal energy from point A to point B, $\Delta E_{T\,AB}$, is directly proportional to the variation in temperature at point B occasioned by point A, ΔT_B, given by Equation (1).

$$\Delta E_{T\,AB} = m_B c_B \Delta T_B \tag{1}$$

where m_B is equal to the mass at point B and c_B the specific heat also at point B.

To express the thermal interaction of the bacteriological incubator with the actuators and the

Figure 2. Graphical representation of the bacteriological incubator system.

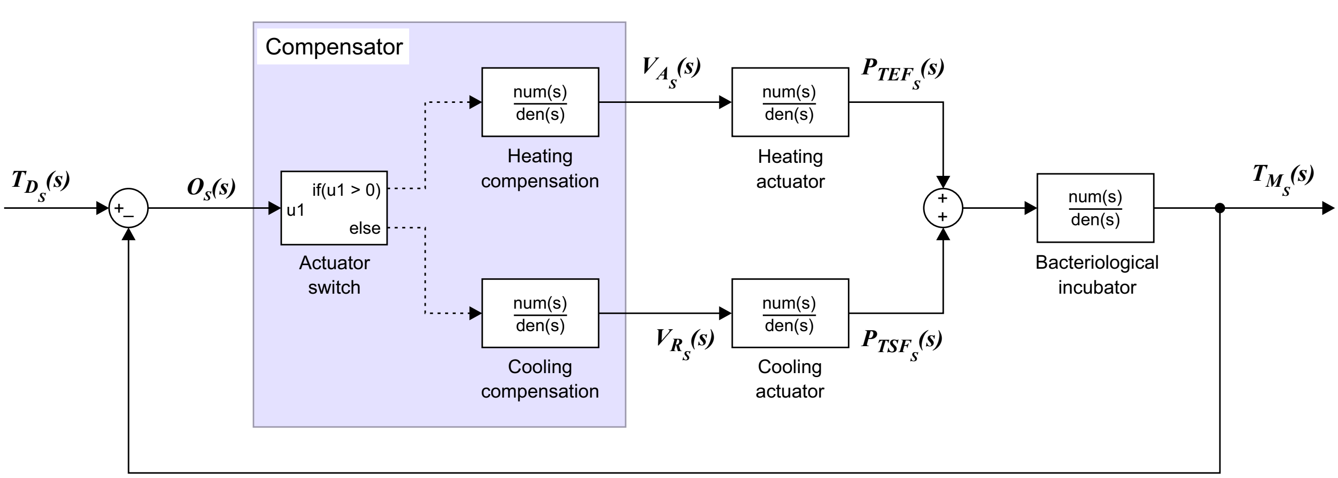


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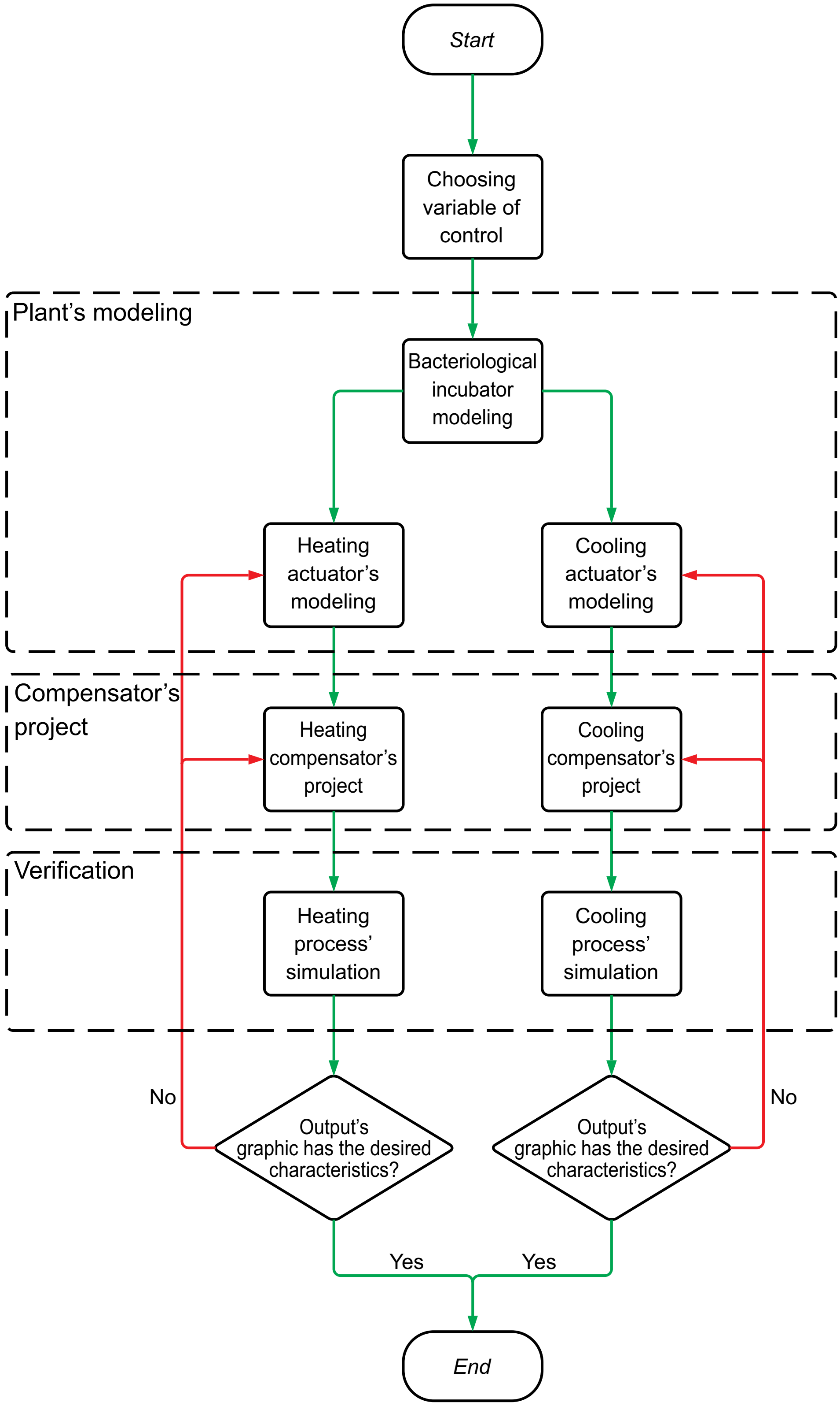
Figure 3. PoC steps' diagram.



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environment, point A is not contained within it and point B is, which expresses the thermal absorption and dissipation by PoC, as shown in Figure 1b. Besides, taking unit time steps, the thermal power is equal to expression 1 and considering the PoC has a constant volume and operation environment, which means m_{inc} (interior mass of the bacteriological incubator) and c_{inc} (interior specific heat of the bacteriological incubator) constant, we arrive at Equation (2).

$$P_T(t) = \frac{dE_T(t)}{dt} = m_{inc}c_{inc}\frac{dT_M(t)}{dt} \tag{2}$$

The average temperature $T_M(t)$ inside the bacteriological incubator, using the arithmetic mean, is equal to the sum of the temperatures of the n point objects present inside it, $T_n(t)$, divided by their quantity (which comprises the volume V of the PoC itself), as described in Equation (3).

$$T_M(t) = \frac{\sum_{n=1}^{k} T_n(t)}{V} \tag{3}$$

Since the inside of the bacteriological incubator consists more of air than something else, the mass inside it is calculated as a function of air density, d_{ar}. Thus, the thermal capacitance C_T of the PoC is given by Equation (4).

$$P_T(t) = L^3 d_{ar}c_{ar}\frac{dT_M(t)}{dt}$$

$$P_T(t) = C_T\frac{dT_M(t)}{dt} \tag{4}$$

The thermal power that interacts with the bacteriological incubator, $P_T(t)$, is the sum of the thermal powers from the environment and the actuators, named natural thermal power, $P_{T_N}(t)$, and forced thermal power, $P_{T_F}(t)$, respectively, given by Equation (5).

$$P_{T_N}(t) + P_{T_F}(t) = C_T\frac{dT_M(t)}{dt} \tag{5}$$

Natural thermal power is directly proportional to the variation between the average temperature inside the bacteriological incubator and the environment temperature. Considering the heat transfer process by thermal convection occurs in the bacteriological incubator at each unit time interval, this calculates according to Equation (6).

$$P_{T_N}(t) = h_{ar}A\big(T_A(t) - T_M(t)\big) \tag{6}$$

where: $T_A(t)$ is the environment temperature and $R_T = \frac{1}{h_{ar}A}$ the thermal resistance, given by the inverse of the product between the area A, perpendicular to the plane in which the thermal energy transfer occurs, and the thermal convection coefficient h_{ar}.

Substituting Equation (6) into equation (5), comes the ordinary differential equation (ODE) that expresses the thermal dynamics of the PoC, as described in Equation (7).

$$\frac{dT_M(t)}{dt} + \frac{T_M(t)}{R_T C_T} = \frac{T_A(t)}{R_T C_T} + \frac{P_{T_F}(t)}{C_T} \tag{7}$$

In this work, the bacteriological incubator operates in an environment where the temperature is constant. Applying the Laplace transform, the transfer function of the process results in Equation (8).

$$\frac{T_{M_S}(s)}{P_{T_{F_S}}(s)} = \frac{1}{C_T}.\frac{1}{s + \frac{1}{R_T C_T}} \tag{8}$$

<u>Heating Actuator Modeling</u>

The actuator for heating the interior of the bacteriological incubator used in this work is an incandescent lamp, for illustrative purposes. The effective thermal power, $P_{T_{E_F}}(t)$, is a percentage of the electrical power present in the incandescent lamp, $P_S(t)$, associated with the useful energy conversion process, according to Equation (9).

$$P_{T_{E_F}}(t) = \eta P_S(t) = \frac{\eta}{R_A}V_A^2(t) \tag{9}$$

where $V_A(t)$ is the voltage source and R_A the electrical resistance of the incandescent lamp. In addition, η expresses the conversion factor, with $0 \leq \eta \leq 1$.

The expression $V_A^2(t)$ is linearized in the operating region from 0 to 150 V (frequently the voltage present in non-industrial places), so the Laplace transform can be applied, presenting operating points equal to 0 and 116,13 V, with R^2 = 86,52%, as outlined in Figure 4.

Thus, the transfer function of the heating actuator in the operating region is according to Equation 10.

$$\frac{P_{TEF_S}(s)}{V_{A_S}(s)} = \frac{116{,}13\eta}{R_A} \quad (10)$$

Cooling Actuator Modeling

In this work, a fan was adopted as an actuator for cooling the interior of the bacteriological incubator, as shown in Figure 1d. The fan has air flow corresponding to the rate of variation of volumetric flow of the fluid perpendicular to the plane that contains it, as described in Equation (11).

$$Q_{AR}(t) = \frac{dV_{AR}(t)}{dt} = A_{ST}v(t) \quad (11)$$

The fluid velocity has a natural portion ($v_N(t)$) and a forced portion ($v_F(t)$) resulting from the non-action and action of the fan, respectively. Since $v_F(t)$ is directly proportional to the rotation speed at the tip of the fan blades ($v_{rotation}(t)$) and this work addresses the process as LTI, $v_F(t) = k_1 v_{rot}(t)$. Therefore:

$$Q_{AR}(t) = A_{ST}\big(v_N(t) + v_F(t)\big)$$

$$Q_{AR}(t) = A_{ST}v_N(t) + A_{ST}k_1 v_{rot}(t) \quad (12)$$

with $k_1 > 0$.

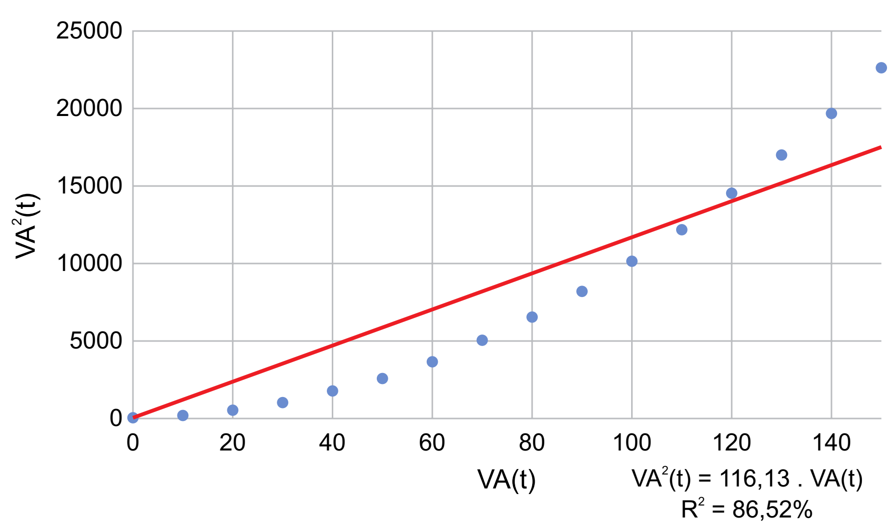
The angular rotation speed of the fan is directly proportional to the rotation speed at the tip of its blades ($v_{rot}(t) = R\omega(t)$), the cross-sectional area, perpendicular to the plane where there is the volumetric air flow, is the area of the circle that comprises the fan blades, see Figure 1d ($A_{ST} = \pi R^2$). Furthermore, $A_{ST}v_N(t)$ expresses the natural volumetric air flow rate (Q_{AR_N}), which is considered constant, and $k_1\pi = k_{vent}$ as a factor related to ventilation, we arrive at Equation (13).

$$Q_{AR}(t) = Q_{AR_N} + k_{vent}R^3\omega(t)$$

$$\frac{Q_{AR_S}(s)}{\omega_s(s)} = k_{vent}R^3 \quad (13)$$

Since the volumetric air flow and the forced output thermal power are directly proportional and, once again, this work addresses the process as LTI, Equation (14) is defined, where $k_T > 0$ and expresses a thermal constant of the fan.

Figure 4. Linearization graphic of $V_A^2(t)$.



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$$\frac{P_{T_{SF_S}}(s)}{Q_{AR_S}(s)} = k_T \tag{14}$$

By taking the product of the transfer expressions in Equations (13) and (14), we arrive at the relationship between the forced output thermal power and the angular rotation speed of the fan, shown in Equation (15).

$$\frac{P_{T_{SF_S}}(s)}{\omega_s(s)} = k_{vent}R^3k_T \tag{15}$$

The angular rotation speed of the fan is caused by the activation of a DC electric motor present in it, modeled as follows:

$$\frac{\omega_s(s)}{V_{R_S}(s)} = \frac{k_m}{R_aJ}.\frac{1}{s+\frac{k_c}{J}} \tag{16}$$

Consequently, by taking the product of Equations (15) and (16), the actuator input-output relationship for cooling is obtained according in Equation (17).

$$\frac{P_{T_{SF_S}}(s)}{V_{R_S}(s)} = G_{vent}\frac{1}{s+\frac{k_c}{J}} \tag{17}$$

where $k_m > 0$ is the motor torque constant, $k_c > 0$ the load torque constant, $R_a > 0$ the armature resistance, $J > 0$ the motor moment of inertia and

$G_{vent} = \frac{k_{vent}k_mk_TR^3}{R_aJ}$ the static gain.

Controller Design

The compensation design of this process relies on P (Proportional), PI (Proportional- Integral) and PD (Proportional-Derivative) controllers, aiming to meet the following performance specifications: time constant in closed loop lower than in open loop; offset in steady state less than or equal to 2% for the step input; and zero natural oscillation.

Tables 1 and 2 describe the controller gains calculated for heating and cooling processes, respectively.

Table 1. Controllers gains for the heating process.

	P	PI	PD
K_p	$\geq \frac{21{,}518R_A}{\eta R_T}$	$> \frac{0{,}0086R_A}{\eta R_T}$	$\geq \frac{21{,}518R_A}{\eta R_T}$
K_i	0	$\frac{K_p}{R_TC_T}$	0
K_d	0	0	$R_TC_TK_p$

Table 2. Controllers gains for the cooling process.

	P	PI	PD
K_p	$\geq \frac{2499k_c}{G_{vent}R_TJ}$	$\leq \frac{C_T\left(\frac{k_c}{2J}\right)^2}{G_{vent}}$	$\frac{K_d}{R_TC_T}$
K_i	0	$\frac{K_p}{R_TC_T}$	0
K_d	0	0	$\geq \frac{2499k_cC_T}{G_{vent}J}$

Results

To verify the developed mathematical model, a case study for a commercial bacteriological incubator was assumed, so to evaluate the dynamic behavior of this equipment.

Bacteriological Incubator Characteristics

The BF115 bacteriological incubator, manufactured by BINDER, is adopted as a reference [7]. It has a heating time to 37 °C of 480 seconds (8 minutes), information shown in the datasheet as “Heating up time to 37 °C”, and this is the establishment time t_s for the step input.

From this information, the time constant of the open loop process (τ) is a quarter of the value of the settling time, resulting in $\tau = R_TC_T = 120$ seconds (2 minutes).

For the other constants, an incandescent lamp with a 90% conversion factor (η), a 100 W power module for 110 Vrms AC power, resulting in $R_A = 242\ \Omega$, and a household fan with 15 cm radius and average measurements found in the market for the other constants.

All parameter values used in the simulation are present in Table 3.

Computer Simulation

From the system parameters described in Table 3, the bacteriological incubator was simulated in MATLAB/Simulink 2024b software, applying P, PI and PD controllers in the closed-control loop, whose gains obtained for heating and cooling processes are presented in Table 4 and 5, respectively.

In heating process simulation shown in Figure 5, the P, PI, and PD controllers simultaneously meet the performance specifications. However, P and PD present gains that accelerate the setpoint tracking process, which consequently requires actuator efficiency that makes it inconvenient for practical implementation. In contrast, the PI presents an acceptable response, both for the design requirements and practical implementation, thus indicating the choice among the controllers mentioned.

For the cooling process shown in Figure 6, the P and PI controllers cannot simultaneously meet these three design requirements. For the P controller, one must choose to either nullify the natural oscillation or respect the offset requirement. For the PI controller, due to the controller's zero offset with the bacteriological incubator pole and the selected measurements for the simulation constants, the closed-loop time constant requirement for the process is not met.

In contrast, the PD controller simultaneously meets all the performance specifications; however, it offers gains that accelerate the setpoint tracking process, making it inconvenient for practical implementation. Furthermore, despite the PD controller's null natural oscillation, a sudden setpoint change causes oscillation in the output due to the process's setpoint tracking speed. In short, none of these three controllers are recommended for implementation in healthcare equipment.

Table 3. Parameter values used in simulation for bacteriological incubator compensation.

Bacteriological incubator	Incandescent lamp	Fan
R_T = 0.83	η =0.9	G_{vent} = 0.03
C_T = 144.46	R_A = 242	k_c = 0.0001
		J = 0.007

Table 4. Controller gains for heating process simulation.

	P	PI	PD
K_p	7000	10	7000
K_i	0	0.083	0
K_d	0	0	840000

Table 5. Controller gains for cooling process simulation.

	P	PI	PD
K_p	1200	0.12	1250
K_i	0	0.001	0
K_d	0	0	150000

Conclusion

This work modeled and simulated a bacteriological incubator, aiming at setpoint tracking and characteristics found in commercial versions of the equipment.

For future work, it is recommended to add noise to the process loop and PID compensation to assess output behavior due to unwanted inputs, such as ambient temperature variations, and to assess how optimized the PID is compared to the others mentioned in this work for this process.

Figure 5. Heating process curve response.

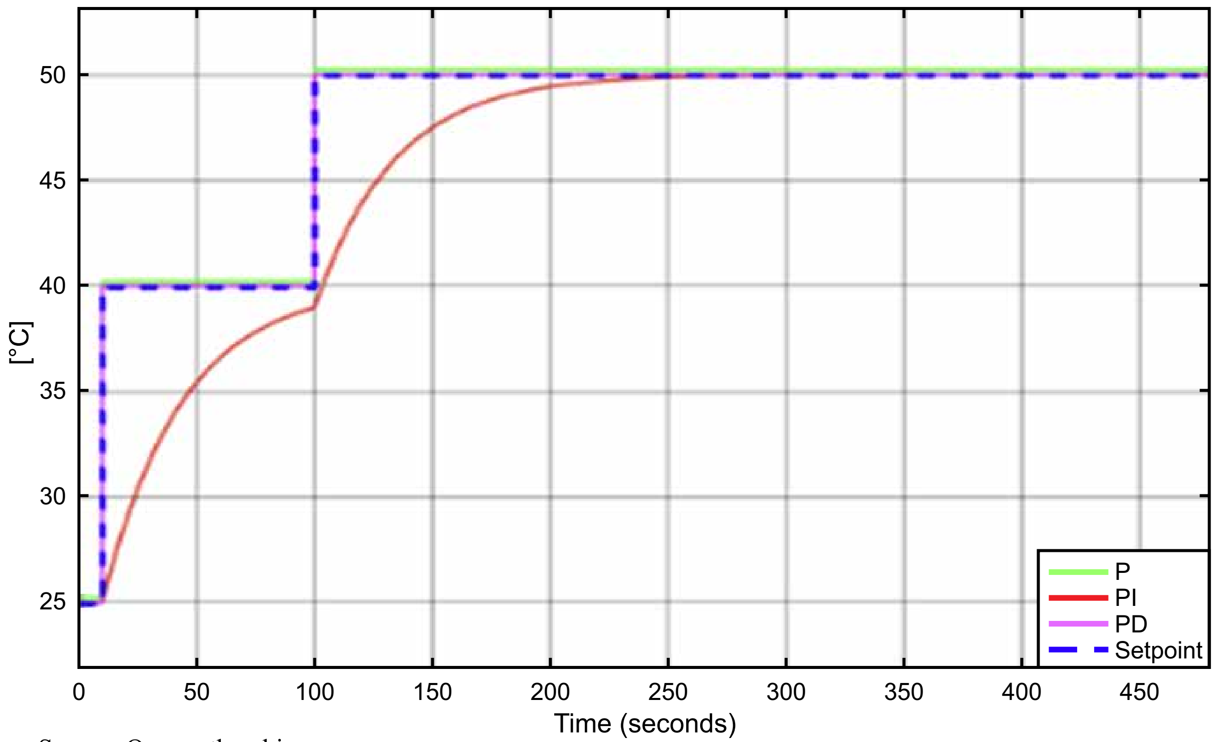

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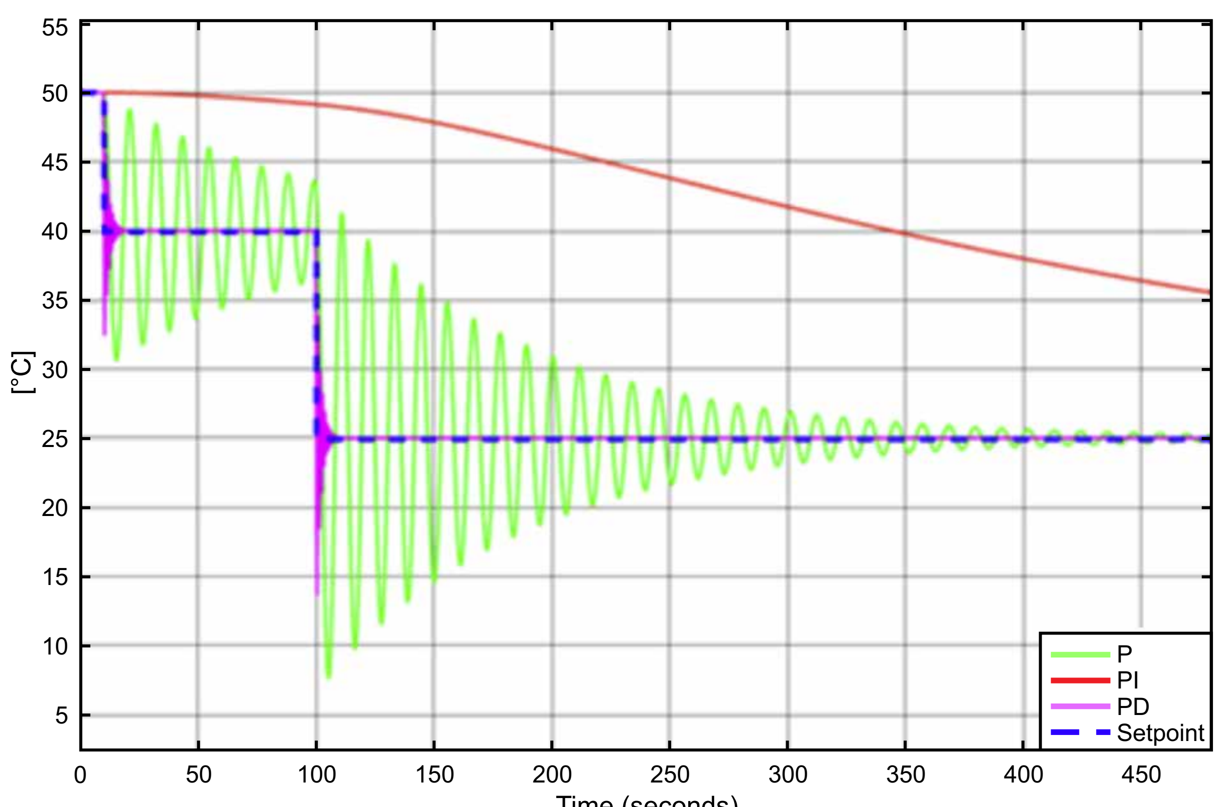
Figure 6. Cooling process curve response.



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Furthermore, we propose producing a prototype of this process to further verify the results presented in this work.

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Performance Analysis of an LCL Filter with Active Damping and Resonant Control for Grid-Connected Inverter

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The growth of Distributed Generation (DG) from renewable energy sources significantly impacts the operation of electrical power systems. To enable the efficient integration of these sources into the electrical grid, inverters play a fundamental role by converting direct current (DC) into alternating current (AC). This study aims to present a simplified design project, implemented and tested through simulations in the MATLAB Simulink environment. The goal is to make resonant control techniques and active damping through capacitor current feedback more accessible and easier to understand, as well as to evaluate and demonstrate the effectiveness of the proposed methods, enabling their practical application. The results obtained showed that the control techniques employed are essential to ensure stability and power quality in inverters with LCL filters. The methodology was presented in a clear and objective manner, facilitating understanding. The simulations highlighted the reduction of the resonance peak, the effective control of the current injected into the grid, and low THD values, confirming the feasibility of applying these techniques in renewable energy systems connected to the electrical grid.
Keywords: Inverters. LCL Filter. Active Damping. Resonant Control.

The growth of Distributed Generation (DG) from renewable energy sources significantly affects the operation of electrical power systems. The increasing penetration of photovoltaic, wind, and other grid-connected DG technologies requires viable strategies to mitigate such impacts related to harmonic distortion and stability [1].

In this context, the efficient integration of renewable energy generation systems into the electrical grid requires the use of inverters, whose primary function is to convert direct current (DC) into alternating current (AC) with high dynamic performance and compliance with power quality standards [2]. To meet these standards, filters are employed. Among the most commonly used types are the inductive (L) filter, applied in low-power systems and characterized by its simple design; the inductive-capacitive (LC) filter, which provides better harmonic reduction performance than the L filter; and the inductive-capacitive-inductive (LCL) filter, which offers the highest efficiency in attenuating high-frequency harmonics. The most widely used filter topology is the LCL, designed to attenuate high-frequency harmonic components generated by pulse width modulation (PWM) and to ensure the injection of current with low harmonic content.

The LCL filter can be implemented using passive or active damping techniques. In the passive approach, resistors are inserted — either in series or in parallel with the inductive and capacitive elements — with the purpose of dissipating energy at the resonance frequencies. Although simple to implement, this technique results in additional power losses due to the Joule effect, which negatively impacts the overall efficiency of the converter [3].

The active damping, on the other hand, incorporates control strategies capable of suppressing filter resonance without introducing resistive losses, as in the case of capacitor current feedback. This approach improves system stability and preserves energy efficiency. However, it increases the complexity of the control design due

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to the dynamic coupling between the damping action and the inverter current control loop, which may reduce stability margins [3].

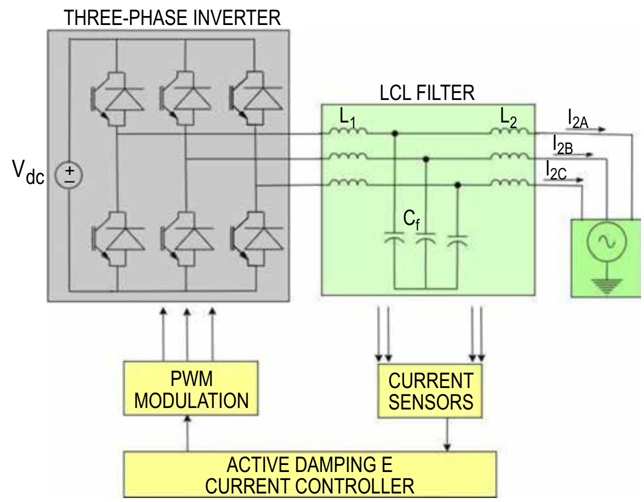
This work presents the steady-state performance analysis of a control system applied to a grid-connected inverter equipped with an LCL filter and active damping through capacitor current feedback, combined with a resonant-type current controller [4]. A simplified design procedure is proposed to facilitate implementation and validation through simulations in the Simulink/MATLAB environment, making the control techniques more accessible and understandable, as well as quantitatively evaluating their effectiveness and demonstrating their feasibility for application in renewable energy systems connected to the electrical grid.

System Modeling

The design and sizing of the proposed system follow the methodological guidelines described in [4], ensuring consistency among modeling, implementation, and validation, in accordance with well-established methodologies recognized in the specialized literature, thereby reinforcing the relevance and reliability of the adopted approach. The modeled electrical circuit consists of a three-phase inverter connected to the power grid through an Inductor–Capacitor–Inductor (LCL) filter, associated with a resonant control system composed of active damping and a current controller. This controller is responsible for regulating the three-phase currents I_{2A} , I_{2B} , and I_{2C} (see Figure 1).

In Figure 1, the presence of current sensors can be observed, which provide information to the digital control system that, in turn, determines the logical state of the inverter's electronic switches. It is worth noting that the renewable energy source at the inverter input is represented by an ideal direct voltage bus (VDC), while the grid is represented by its Thevenin equivalent. In this work, the LCL filter is used to attenuate high-frequency harmonics generated by the modulation process, ensuring that the current injected into the grid has a low total

Figure 1. Proposed electrical system.



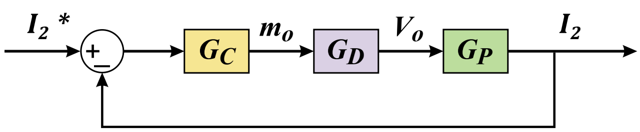
harmonic distortion (THD) as established by IEEE 519. Another important feature is that this type of filter exhibits a characteristic attenuation of 60 dB/decade, making it generally suitable for designs requiring compact components. However, the LCL filter introduces a resonance peak between the cutoff frequency and the switching frequency, requiring the use of damping techniques—in this study, active damping via capacitor current feedback—to ensure system stability and robustness.

Control System Stability

The stability analysis of the converter current control system begins with obtaining the transfer function of the LCL filter without damping, considering a reference current I_2^* (Figure 2). This modeling allows for the evaluation of the system dynamics and the identification of stability conditions prior to the inclusion of active damping [4].

In the block diagram, the G_C subsystem represents the resonant current controller, responsible for adjusting the error between the measured current and the reference. The G_D subsystem models the behavior of the modulation process and its dynamic effect on the inverter switches. This block includes the delays introduced by the analog-to-digital conversion of the current. The G_P subsystem

Figure 2. Block diagram of the I_2 current control without damping.



describes the plant represented by the LCL filter, considering the electrical parameters obtained from the design. This modular approach enables the application of frequency-domain analysis techniques (Bode diagrams) for the evaluation of gain and phase margins, robustness, and dynamic performance, allowing fine-tuning of the control parameters to ensure stability and low THD of the current injected into the grid in accordance with power quality standards.

The G_C block is represented in continuous time by:

$$G_C(s) = K_p\left(1 + \frac{1}{T_r\left(s^2+\omega_0^2\right)}\right) \tag{1}$$

where K_P is the proportional gain and T_R is the time constant, both of which need to be properly tuned. In addition, ω_0 represents the fundamental frequency of the electrical grid.

The G_D transfer function is required to represent the time delay that occurs in the inverter when controlled by PWM modulation, as this switching does not occur instantaneously.

In Equation 2, T_D can be approximated as 1.5 times the sampling period T_S.

$$G_D(s) = V_{dc}e^{-sT_d} \tag{2}$$

For the G_P block, which represents the behavior of the LCL filter, the following transfer function is obtained:

$$G_P(s) = \frac{I_2(s)}{V_0(s)} = \frac{\gamma_{LC}^2}{sL_1(s^2+\omega_r^2)} \tag{3}$$

where $\gamma_{LC} = \sqrt{1/\left(L_2C_f\right)}$ and $\omega_r = \sqrt{L_1 + L_2/L_1L_2C_f}$ refers to the resonance frequency of the filter.

The internal current control loop is not limited to attenuating the gain peak associated with the resonance frequency of the LCL filter; it also plays a crucial role in expanding the system's stability regions, thereby increasing its robustness against parametric variations. From the Bode diagram analysis of the transfer function illustrated in Figure 2 — corresponding to the system without damping — it can be observed that system stability is directly related to the positioning of the filter's resonance frequency. More specifically, the system remains stable when it is within the range between $f_c/6$ and $f_c/2$, with the critical frequency defined as $f_c = 1/T_S$, as shown in Figure 3 [5].

Figure 3 presents the Bode diagram for four different resonance frequency values, showing that f_1 and f_2 are located in the unstable region, while f_3 and f_4 fall within the stability range predicted by the analysis. This characterization not only allows the evaluation of the system's dynamic performance but also enables the definition of design criteria for the correct positioning of f_r , in order to avoid critical phase crossings that could compromise the stability margin.

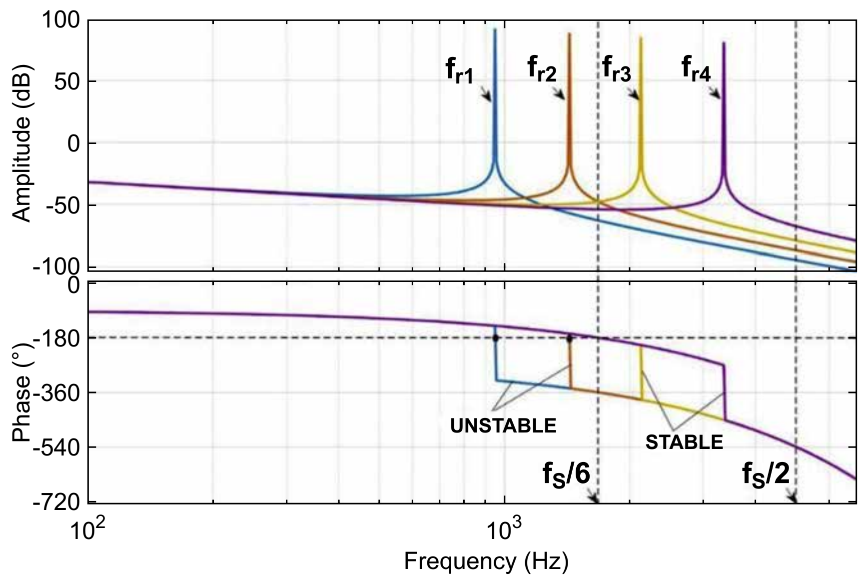
An alternative to stabilize the control system with a resonance frequency lower than the critical frequency is the strategy known as active damping. In this approach, an internal loop is added to the control system with the purpose of attenuating the resonance phenomenon. The capacitor current was used as the feedback variable for active damping. The scheme, in terms of a block diagram, is presented in Figure 4. In this diagram, the transfer functions G_{ic} and G_{i2} are added, which are derived from G_P. The parameter K is a damping gain to be adjusted in the control design, where:

$$G_{iC}(s) = \frac{1}{sL_1}\frac{s^2}{s^2+\omega_r^2} \tag{4}$$

$$G_{i2}(s) = \frac{\gamma_{LC}^2}{s^2} \tag{5}$$

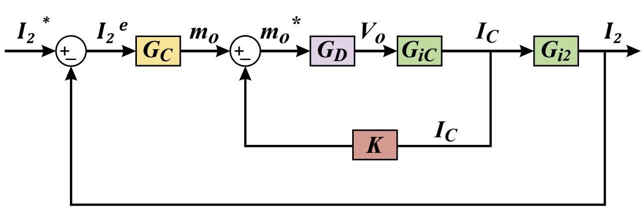
The Figure 5 again shows the Bode diagram after the application of active damping, plotted for the same four resonance frequencies as in Figure 3. We observed that this technique provides significant

Figure 3. Bode diagram of the system without damping.



Source: Oliveira and colleagues (2019) [8].

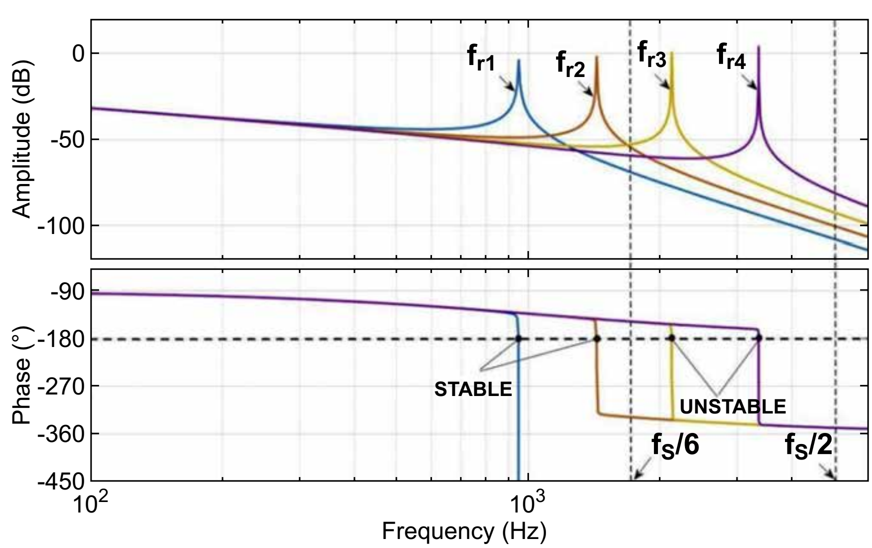
Figure 4. Block diagram of the I_2 current control with active damping via capacitor current feedback.



attenuation of the resonance peak magnitude, reducing the excessive gain at f_r.

With the inclusion of active damping, a swapping between the stable and unstable regions can be observed compared to the case without damping. Specifically, the frequencies f_{r1} and f_{r2}, previously located in the unstable region, now exhibit stable conditions, while f_{r3} and f_{r4}, formerly stable, become unstable. The swapping of these zones can

Figure 5. Bode diagram of the system with damping



Source: Oliveira and colleagues (2019) [8].

be advantageous, as it allows the expansion of the stability region through additional strategies, such as the use of a phase-lead compensator capable of increasing the critical frequency [6]. Thus, the results can be summarized as follows:

$$\forall f_r \in R,\ f_r < \frac{f_c}{6} \Rightarrow Stable\ System \quad (6)$$

Thus, the expansion of the stability region facilitates the tuning process of the resonant current controller parameters (K_P and T_r), increasing the range of viable parameter combinations that ensure system stability.

Resonant (PR) Controller Design

As seen in [4], the design of K_P, T_r, and K is carried out using the pole-placement technique and root locus analysis. The system's frequency response must satisfy a desired gain margin at the phase crossover frequency (ω_C), safely greater than 6 dB, and a phase margin between 45° and 60° (ϕ_m), to ensure controllability. Thus, it is necessary to heuristically set values of ω_c to achieve a frequency response that meets the phase margin specification ϕ_m. It is worth noting that a good starting point is to use ω_C values close to those given by Equation 7, which are determined from the analysis of the I_2 (output) and I_2 (current error) currents, as shown in Figure 4. From the value of ω_C, the gains K_P and T_r are obtained according to Equations 8 and 9, which are also determined from the Block Diagram analysis expressed in Figure 4. Following the methodology and derivations in [4], a value of K can then be selected based on the limits established by the filter parameters. However, in this work, the possible values of K were determined heuristically, taking into account the criteria for the aforementioned gain and phase margins.

Table 1. System parameters.

Parameter	Value
L_1 (H)	0.00763433
L_2 (H)	0.00458060
C_f (F)	0.00000393
f_c (Hz)	10000
f_r (Hz)	1500.9379
T_r (s)	0.0032
K_p	38.3476
V_{dc} (V)	325

$$\omega_C = \frac{\frac{\pi}{2} - \phi_m}{\frac{3Ts}{2}} \quad (7)$$

$$K_P \approx \frac{\omega_C\left(L_1 + L_2\right)}{V_{dc}} \quad (8)$$

$$T_r = \frac{10}{\omega_C} \quad (9)$$

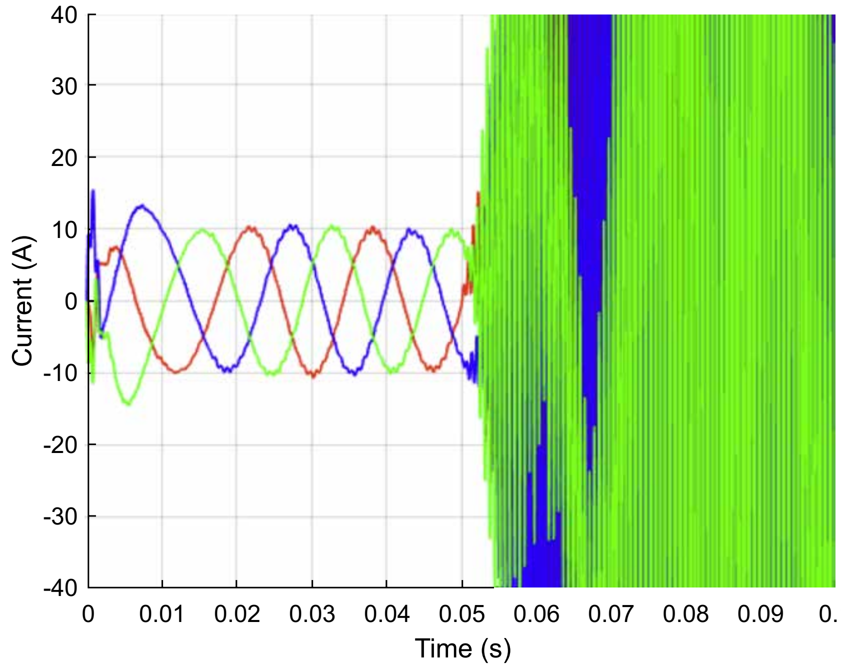
Simulation Results

In this section, the results obtained through simulations conducted in the MATLAB Simulink environment under steady-state conditions are presented. The simulations were carried out using the parameters shown in Table 1, which summarizes the design of the LCL filter and the resonant controller. To ensure effective damping of the system, it was stipulated that $f_r < f_c / 6$, in addition to selecting a phase margin (ϕ_m) between 45° and 60°.

Output Current Behavior of the LCL Filter

The Figure 6 shows the current waveforms of the three phases of the system over time. It can be observed that, up to 0.05s, with active damping enabled, the waveforms are sinusoidal, symmetrical, stable, and maintain an amplitude around 10A, indicating that the controller was able to satisfactorily track the current reference. However, from 0.05s onwards, with the deactivation of active damping, there is an abrupt and significant increase in the current amplitudes, exceeding 30A, resulting in a progressively oscillatory behavior and consequent system instability.

Figure 6. System simulation with damping Enabled and Disabled at 0.05s



The impact of deactivating active damping on the system can be clearly observed, as evidenced by the uncontrolled behavior of the currents. The removal of the damping loop causes the amplification of the LCL filter's resonance peak, which then operates within an unstable region, resulting in increasing oscillations and loss of system stability. This phenomenon highlights the critical importance of active damping strategies, such as capacitor current feedback, which shift the resonance pole to a stable region of the complex plane, expanding the system's stability zone. In this way, robust and stable operation of the inverter is ensured, even in the presence of parametric variations and adverse operating conditions.

Resonant Control (PR) Performance

In Figure 7, a comparison is made between the reference current (I_2*) and the measured output current (I_2), controlled by a resonant (PR) controller. The controller demonstrates a high tracking capability, with an almost negligible tracking error, resulting in an almost perfect overlap between the measured current and the reference. Both exhibit sinusoidal characteristics with low harmonic distortion, highlighting the effectiveness of the PR controller in ensuring dynamic accuracy and the quality of the current injected into the system.

Total Harmonic Distortion (THD) Analysis

The Figure 8 presents the THD results measured in the output current of the LCL filter, i.e., the current directly injected into the distribution grid. From the beginning of the simulation up to 1 s, active damping is in operation, keeping the THD below 5% and fully complying with the limits established by IEEE 519 (5%) and ANEEL PRODIST – Module 8 (10%) [2], [7], which demonstrates high power quality. After 1 s, due to the deactivation of damping, system instability occurs, causing the THD to rise above 40%. These results confirm that active damping is not only fundamental for dynamic stability but also essential to ensure that the injected current remains within the harmonic distortion limits established by power quality standards.

Figure 7. I_2 Current control.

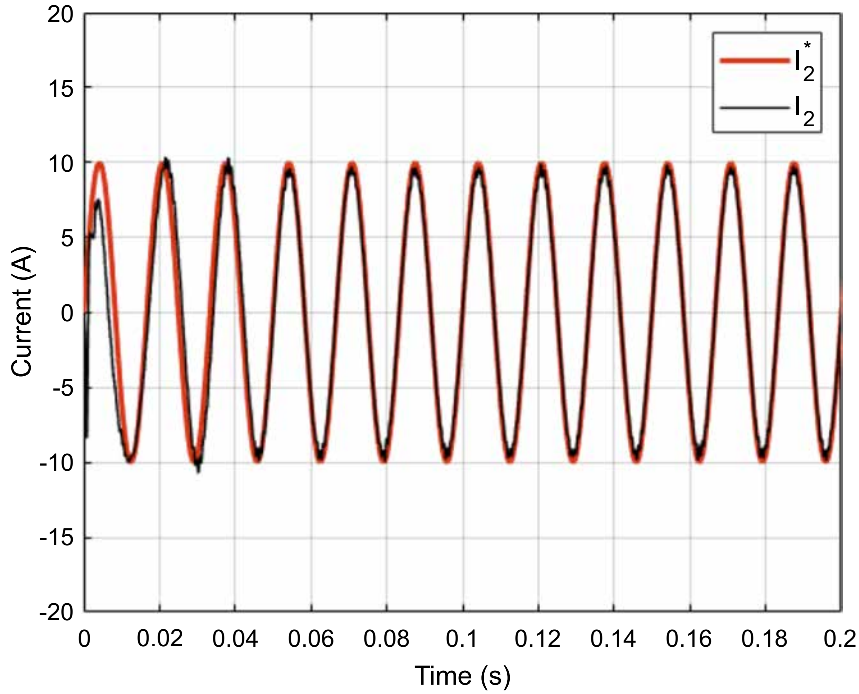
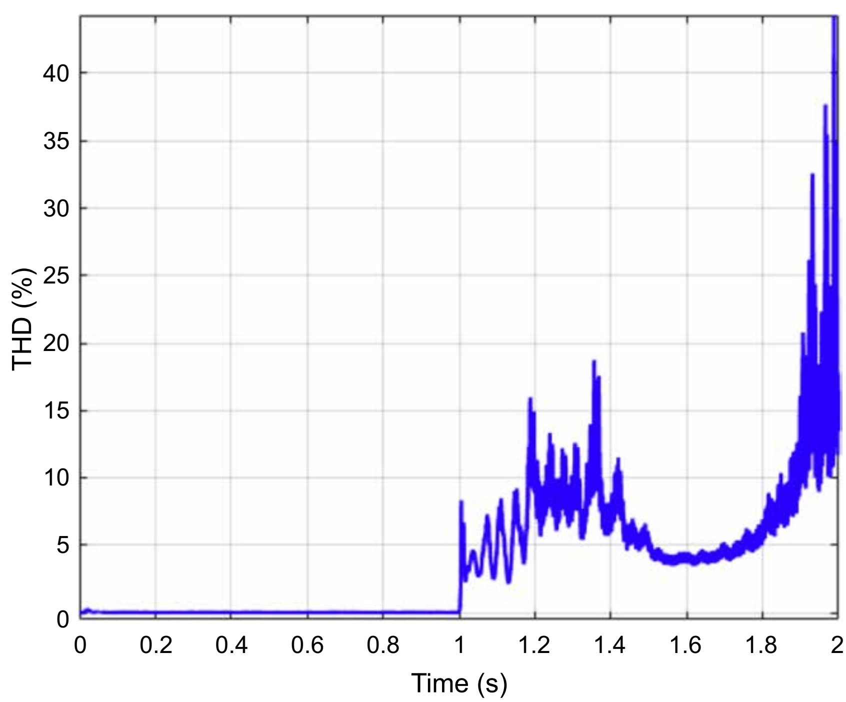


Figure 8. System THD with control enabled and disabled at 1s.



Conclusion

This paper presented a study on the simplified design of a resonant (PR) controller combined with an active damping scheme implemented via capacitor current feedback, following the procedures described in the established literature, as detailed in [4]. The results demonstrate that the use of active damping through capacitor current feedback, together with the PR controller, is essential to ensure dynamic stability and power quality in grid-connected inverters with LCL filters.

The methodology adopted for the development of these control techniques was described in a clear and structured manner, facilitating their understanding and practical application. The simulations demonstrated effective attenuation of the resonance peak, precise regulation of the current injected into the grid, and maintenance of low THD levels, meeting the regulatory requirements. These characteristics make the proposed solution technically feasible for applications in grid-connected renewable generation systems.

For future works, it is recommended to extend the analyses to the transient regime in order to evaluate the dynamic behavior of the system under different operating conditions. In addition, the application of other design and sizing methodologies, also recognized in the literature, could be considered to complement or enhance the results obtained in this study.

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Neurobypass 1.0: A Mechanical Approach on 3D-Printed Neurocontrolled Hand Orthosis for Subacute Post-Stroke Rehabilitation

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Stroke is one of the leading causes of motor disability worldwide, directly impairing limb functionality and compromising individuals' independence in daily activities. Stroke-induced hand paresis requires assistive devices whose kinematics, compliance, and morphology faithfully emulate healthy biomechanics. Neurobypass 1.0, under SENAI CIMATEC's ReaPTA 5.0 programme, delivers a patient-personalized hand orthosis neuro-controlled by EEG that is engineered around three mechanical pillars: biomimicry, human-like motion and additive manufacturing. The technology integrates electroencephalography (EEG) to command robotic elements via recognition of neural motor-intention patterns, additive manufacturing with flexible and rigid materials (TPU/PLA) and an immersive virtual-reality environment, delivering neurofeedback that stimulates neuroplasticity. By fusing brain-computer-interface (BCI), multi-material 3D printing, modular biomimetic geometry and minimum jerk kinematics into a single, low-cost platform tht amplifies the therapeutic impact alongside conventional therapy, providing clinicians with an evidence-driven, easily serviceable device to accelerate upper-limb functional recovery in post-stroke patients.
Keywords: Brain-Computer Interface. Stroke Rehabilitation. Hand Exoskeleton. Motor Imagery. Additive Manufacturing. Motor Imagery. Neuroplasticity. Robot-Assisted Therapy. OpenBCI.
Abbreviations: EEG, electroencephalography. BCI, brain-computer interface. ROM, range of motion. PLA, polylactic acid. TPU, thermoplastic polyurethane. MCP, metacarpophalangeal. MVC, maximal voluntary contraction. DCL, dynamic control law. VR, virtual reality.

Stroke is one of the leading causes of motor disabilities worldwide, significantly compromising upper limb function and individuals' independence in daily activities [1]. Hand paresis represents a recurrent and difficult-to-rehabilitate condition, requiring therapeutic approaches that integrate biomechanics, neurophysiology, and sensorimotor factors to the functional recovery process [1-3].

Over the past decades, advances in brain-computer interfaces and motor imagery techniques combined with sensory feedback have considerably expanded the potential of assistive technologies for post-stroke rehabilitation. Rehabilitation systems that incorporate recognition of motor intention via electroencephalography, robotic devices and immersive environments have proven effectiveness in modulating neuroplasticity into recovering residual corticospinal pathways, promoting adaptive functional neuro reorganization [4-6].

There is consistent evidence that task-oriented training strategies, when integrated with wearable sensors and robotic systems, contribute to improve motor accuracy and functional performance, while chronic patients may not experience such benefits, sub-acute patients do benefit from exoskeletal gait training alongside traditional therapy [3,7].

Within this context, the present work aims to present the development and technological basis of the "Neurobypass 1.0" a neuro-controlled robotic hand orthosis, through additive manufacturing and OpenBCI platform. It seeks to deliver an accessible, personalized, biomimetic, and clinically replicable solution for upper limb rehabilitation in the subacute phase of stroke, aligned with scientific evidence and normative guidelines [2,8,9].

Materials and Methods

This study begins with a State-of-the-Art review about rehabilitation orthosis. Grounded in

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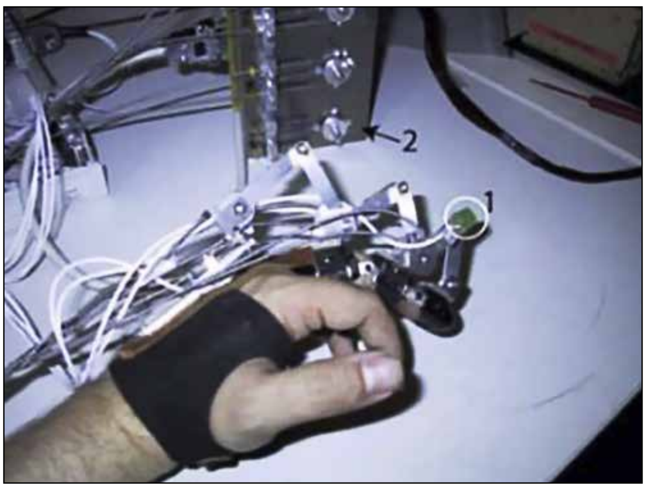
multidisciplinary integration between engineering and clinical rehabilitation. The methodological configuration aligns with scientific practices in Germany, China and the United States of America [9-11].

Figure 1. Exoskeleton for rehabilitation.



Source: Wege and colleagues [10].

References were selected from indexed databases such as PubMed, Scopus, IEEE Xplore and Web of Science, ensuring scientific relevance and reliability, by using keywords such as Brain-computer interface, Motor Imagery, Stroke rehabilitation, Neuroplasticity, Robot-assisted therapy and OpenBCI.

The selected literatures address neuroplasticity, brain computer interfaces, additive manufacturing, and biomechanical modelling of artificial limbs for rehabilitation [1,13,14].

Figure 2. 3D printed prosthetics for kids.

Source: Grundmandis [12].

Clinical and ergonomic aspects were extracted from experimental research and articles on post-stroke motor recovery, particularly concerning motor imagery training, corticospinal reorganization, and assistive robotics [6,7].

Engineering aspects such as material selection, mechanical properties, and validation procedures followed technical norms and consolidated protocols in biomechanical testing [2,9,15].

<u>Global Function</u>

The global function of the system was defined as the execution of opening and closing the affected hand using robotic assistance and motor intention recognition of patients with post-stroke hand paresis (within the sub-acute period). The device acts as mediator between neural movement intention (decoded via EEG and machine learning) and the movement itself of the affected hand (Figure 1) [3,4].

To increase adaptability and prosthetic embodiment, the design complies with biomechanical limitations, user comfort (ergonomics) and human-like controlled movement. This goal aligns with evidence indicating that assistive devices integrated with brain–computer interfaces enhance motor recovery when combined conventional therapy and motor imagery recognition and sensory feedback within virtual environments (Figure 2) [5,6].

<u>Functional Synthesis</u>

The functional synthesis of the Neurobypass 1.0 exoskeleton focuses on the integration of biomechanics, ergonomics and neuro-assisted control.

The system's functional breakdown resulted in four main sub-functions:

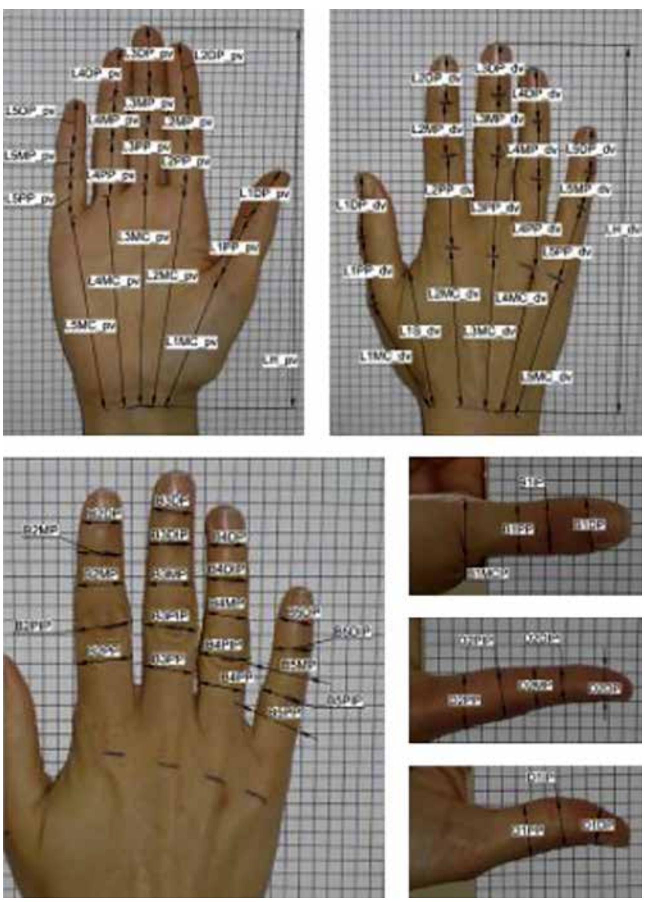
(I) Ergonomic fixation of the orthosis to the upper limb.
(II) Passive-assisted articulation of the fingers.
(III) Mechanical transmission of controlled flexion movement.
(IV) Neuro-assisted triggering via cortical signals.

Concept Generation

The synthesis process was guided by Spanish anthropometric data and ergonomic requirements of comfort, safety, and structural lightness[2,16,17].

The concept generation phase included selection criteria such as structural modularity, biomimicry, adaptable anthropometry, low weight and cost, selective rigidity, and compatibility with 3D printing for personalization (Figure 3) [9,16,17].

Figure 3. Hand measurements.



Source: Vergara and colleagues [16].

These concepts were selected to ensure compatibility with real clinical application, optimizing reproducibility, ergonomics, and safe integration with neuro-controlled systems, thus validating the technical foundations for future development stages [14].

Morphological Matrix

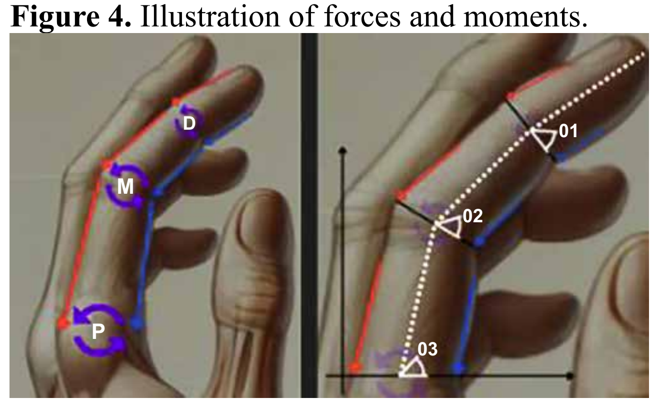
In the conceptual mechanics stage of the project, the Morphological Matrix was developed to support the dimensional and functional parameters necessary for the biomechanical modelling of a hand exoskeleton.

The selected parameters include muscle force, joint torque, moment of inertia, angular velocity (ω), angular acceleration (α), friction coefficients, joint range of motion (ROM), and movement trajectory.

The architecture shown in Figure 4 aims to ensure the precise transmission of forces from the motor actuators by artificial tendons, allowing the execution of movements compatible with human physiology.

The muscle force capacity of the intrinsic and extrinsic muscles of the hand was defined based on anatomical and physiological data. The force required to simulate intrinsic muscles varies (About 300 N in the flexors and 150 N in the extensors, for fingers phalanges) depending on the muscle group involved, the velocity and its length [9,14].

Figure 4. Illustration of forces and moments.



Joint torque, derived from the product of muscle force and lever arm, was determined using biomechanical models. Upper limb simulations show that torque at the metacarpophalangeal (MCP) joints typically ranges from 0.5 to 2.5 Nm, in functional tasks [2].

Regarding moment of inertia, inertial characteristics of robotic anthropomorphic fingers estimate finger segment inertia between 0.003 and 0.02 kg·m², which is critical for modelling dynamics and control [9,18].

For the angular velocity (ω) and angular acceleration (α) parameters, finite element analyses of portable exoskeletons identify typical angular velocities for finger flexion between 150–250°/s and angular accelerations up to 1000°/s² during high-speed movement. The coefficient of friction between finger-pad and contact surfaces was assumed to vary between 0.45 and 0.85, depending on surface texture and moisture, directly impacting grip force and precision [18,19].

The joint range of motion followed anthropometric data from literature and medical standards, with flexion/extension amplitudes in MCP joints between 0° and 90°, and in interphalangeal joints between 0° and 120° [14].

Finally, the trajectory of movement was based on planar and three-dimensional models simulating natural kinematics during prehension, enabling the refinement of control parameters and the selection of actuation components compatible with the neuromechanical objectives of the project [11].

Biomimicry Movement Control

To ensure physiologically human-like movements, for rehabilitation, this study adopts a control model based on the minimization of jerk (the third derivative of position) [20]. This approach defines that the central nervous system plans voluntary motion by minimizing abrupt acceleration variations, resulting in smoother and more efficient trajectories. This is mathematically formalized through a cost function that penalizes excessive jerk fluctuations, expressed as:

$$J = \int_0^T \sum_{i=1}^{n} \left(\frac{d^3 x_i}{dt^3}\right)^2 \, d_t \qquad (1)$$

This model provides optimal multi-dimensional motion planning by reducing oscillations and improving control in robotic-assisted motor tasks.

Position Equation

Considering boundary conditions with defined initial/final positions and zero velocity and acceleration, the ideal displacement trajectory over time is expressed as:

$$x(t) = D * [6 * \left(\frac{t}{T_f}\right)^5 - 15 * \left(\frac{t}{T_f}\right)^4 + 10 * \left(\frac{t}{T_f}\right)^3] \qquad (2)$$

Velocity Equation

The first derivative of the position yields a smooth, bell-shaped velocity profile, characteristic of natural reaching movements:

$$v(t) = D * [30 * \left(\frac{t}{T_f}\right)^4 - 60 * \left(\frac{t}{T_f}\right)^3 + 30 * \left(\frac{t}{T_f}\right)^2] \qquad (3)$$

Acceleration Equation

The acceleration profile indicates a gradual speed-up and slow-down pattern, minimizing mechanical shocks and maximizing ergonomic comfort:

$$a(t) = \frac{D}{T_f} * [120 * \left(\frac{t}{T_f}\right)^3 - 180 * \left(\frac{t}{T_f}\right)^2 + 60 * \left(\frac{t}{T_f}\right)] \qquad (4)$$

Optimal Duration Equation

The optimal time required for voluntary motion does not scale linearly with distance. Instead, it follows a sublinear cubic relationship defined by:

$$T_f = K * \sqrt[3]{D} \qquad (5)$$

This reflects an efficient motor planning strategy from a neuromechanical perspective.

Incorporating the minimum-jerk model into the Neurobypass 1.0 hand exoskeleton provides a robust mathematical foundation for trajectory generation, allowing for realistic and safe EEG-driven motor assistance.

This approach, coupled with multisensory feedback, promotes cortical reorganization and improves rehabilitation outcomes for post-stroke patients [1,3,5].

Technological Risk Analysis

The primary technological risk identified in the project concerns the potential for self-injury resulting from misalignment between cortical commands and robotic actuation. Since users present with reduced or absent voluntary motor control, the system must strictly respect kinematic and kinetic limits of the hand and forearm during assisted motion.

To mitigate this risk, the exoskeleton was designed with compliance mechanisms and actuation constraints that limit angular excursion to physiological ranges of motion, based on anatomical models and musculoskeletal simulations [2,9,11].

Joint torque is regulated within the safe biomechanical thresholds observed in post-stroke conditions, accounting for changes in tissue resistance and muscular tone [14,21].

Additionally, real-time feedback from the virtual environment and electroencephalographic command analysis provides dynamic control, allowing the system to adjust motion intensity in response to the user's cortical activation level. This neuro-adaptive mechanism ensures that no movement is executed without neural intention, significantly reducing the probability of mechanical overcompensation [3,4].

The exoskeleton structure and materials also follow ergonomic principles to avoid pressure peaks on sensitive regions. Finger articulation components were dimensioned to allow sufficient stiffness for controlled motion while preserving flexibility to absorb impact and misalignment, aiming to reproduce only physiologically safe trajectories. These solutions are aligned with the anthropometric and ergonomic parameters described in the technical literature, with emphasis on modularity, compliance, and soft tissue adaptation [2,10].

Results and Discussion

The technical development phase of the *"Neurobypass 1.0"* is currently at the stage of prototyping, functional validation and optimization. The methodological strategy was guided by principles of personalized assistive engineering, ensuring coherence between biomechanical performance, technological feasibility, and clinical applicability.

Figure 5. "Neurobypass" 1.0 prototype.

The results obtained so far consolidate the system as a low-cost, 3D-printed, neuro-assisted hand exoskeleton with biomimetic architecture and EEG-based control integration. Initial calculations validate the mechanical transmission based on additive manufacturing using PLA and TPU, achieving required balance between structural rigidity and compliant deformation for safe finger actuation. The articulation profile followed the motion curves derived from the minimum-jerk model, confirming compatibility with natural grasping dynamics (Figure 5) [20].

The control architecture, developed on the OpenBCI platform, successfully recognizing motor imagery patterns, for subacute post-stroke profiles, provide consistent actuation triggers in control test scenarios. This integration aligns with evidence on the efficacy of EEG-based BCI for promoting corticospinal reorganization and functional gains [4,5,22].

Furthermore, anthropometric and ergonomic validation confirms optimal fit and comfort, complying with dorsal and palmar geometries of the upper limb for personalized adaptation [16].

From a clinical standpoint, the current configuration addresses fundamental safety concerns regarding torque, angular velocity and joint range of motion, remaining within biomechanical thresholds for subacute rehabilitation [2,9,11,14].

These results position the system as a viable, replicable solution for application in real clinical environments, contributing to an innovative, neurointeractive rehabilitation framework grounded in low-cost technologies and functional neuroplasticity.

Conclusion

The development of the "Neurobypass 1.0" system resulted in a personalized, low-cost, EEG-driven hand exoskeleton that integrates biomimetic mechanics, additive manufacturing, and neuroadaptive control. Structural tests confirmed that the TPU/PLA transmission system delivers compliant yet safe finger actuation, following movement trajectories predicted by the minimum-jerk model [20,21]. Anthropometric validation ensured ergonomic adherence, while mechanical parameters such as torque and range of motion remained within safe biomechanical thresholds for subacute rehabilitation [2,9,16].

These findings establish Neurobypass 1.0 as a replicable, clinically feasible assistive device, advancing the field of neurointeractive rehabilitation through robust, evidence-based engineering and physiological modelling [3].

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Personalized Learning Model for University-Industry Integration Through PBL Problem-Solving

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Modern educational models recommend Problem-Based Learning (PBL) and Adaptive Learning (AL) to increase the alignment of education and work organization. PBL is a technique that focuses on learning through problem-solving. However, understanding how and why PBL works is a current challenge. To advance this issue, systems that personalize learning processes are recommended. The present study developed an AL approach for PBL to align education with industry through problem-solving. The proposed approach is based on ontologies, complex multilayer networks, Bayesian networks, a recommendation system, and multi-agent architecture. The proposed tool consists of descriptive, diagnostic, predictive, and prescriptive models. This tool is available on eduCAPES with guidelines for implementing these models. Reduced PBL planning effort, increased collaboration in the development of innovation projects, enhanced educational quality, and the availability of data for Artificial Intelligence (AI) training are some benefits of this tool. To evaluate the proposed approach, nine graduate students completed the User Experience Questionnaire. The attractiveness, hedonic quality, and pragmatic quality of the models were positively perceived. Therefore, the results showed that students have a positive perception of the model's functions. The present study was limited to experiments with a small sample of students. Evaluation of the perceptions of university, educational administrators, the graduate program, the educational institution, industry, and a larger sample of students is suggested for future studies. Currently, the model is implemented with a set of existing tools. Therefore, studies to develop a platform with a user-friendly interface that integrates the proposed models are recommended.
Keywords: Personalized Learning. Adaptive Learning. Problem-Based Learning. Industry. University.

The current educational landscape is characterized by the emerging concept of social organization known as Society 5.0 [1]. This model is challenged by the emergence of new types of work and the automation of many existing jobs [2]. To address this challenge, 4.0/5.0 educational models have been proposed [3]. These models are based on Problem-Based Learning (PBL) and Adaptive Learning (AL) [3].

PBL is an approach in which students learn by solving problems contextualized within their future professional environment [4]. Collaborative, contextualized, self-directed, and constructive learning are the main functions of this technique [5]. Understanding how and why PBL achieves these functions is a research gap [6]. Therefore, a lack of quality control techniques for PBL educational functions challenges the adoption of this technique.

To address this challenge, AL techniques are recommended for prescribing PBL specifications that achieve previously defined learning outcomes [6]. AL are approaches that adapt learning aspects to student needs to improve their outcomes [3]. The solution proposed by the present study is an AL model to integrate university and industry through PBL problem-solving.

Related Work

PBL has expanded to a variety of courses. Consequently, the initial proposed format of this technique has been modified. Therefore, there is considerable variability in PBL implementations [7]. This variability has challenged research on how and why PBL works (Figure 1) [6,8].

The present study aims to advance the fourth and current wave of PBL research. This wave aims to answer the question: "Why does PBL

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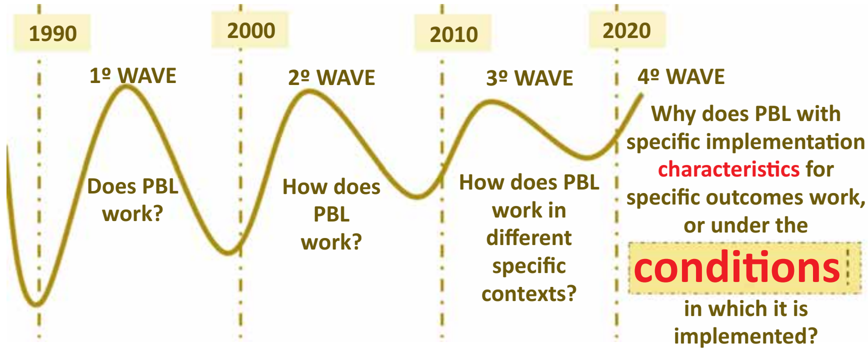
Figure 1. Wave of PBL research.



with particular implementation characteristics for specific outcomes work or not work in the condition where it is implemented?" [6]. The discovery of this period of research was made through a review study of reviews and meta-analyses published between 1980 and 2019 conducted by [6].

To advance this issue, Hung and colleagues [6] recommend the development of theoretical approaches and probabilistic models. Studies that advanced in the fourth wave of research proposed guidelines for developing realist reviews [9], design-based research [10], and causal maps [11]. These studies recommended: the use of personalized approaches [10], the development of repositories [11], the use of AI in causal maps [11], and the investigation of adaptations of PBL approaches [12].

The AL approaches include the adaptation mechanism, student models, content models, and instructional models [13,14,15], as shown in Figure 2. The use of AL approaches for PBL focuses on adapting content [16], curriculum [17], feedback [18], and learning resources [19]. Therefore, there is a gap in AL development that advances the issue of the fourth wave of PBL research.

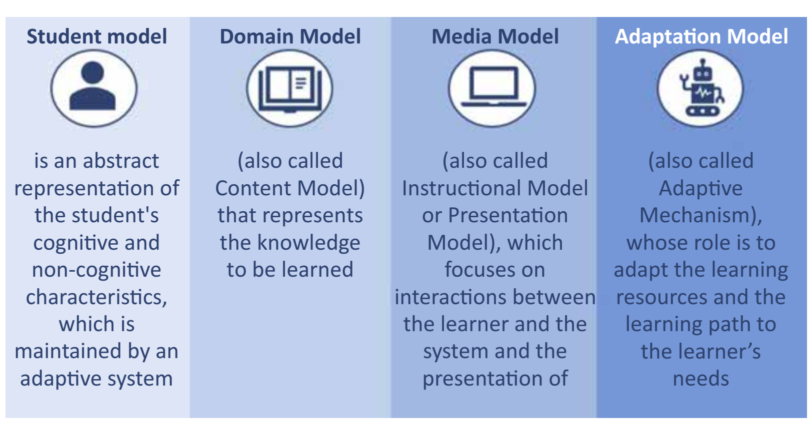
Materials and Methods

The AL approach proposed in this study encompasses descriptive, diagnostic, predictive, prescriptive, integrative, and evaluative models, as illustrated in Figure 3.

The ontologies will be used in the descriptive model. These data structures allow the representation of concepts within a given domain [20,21]. The complex multilayer networks will substantiate the diagnostic model.

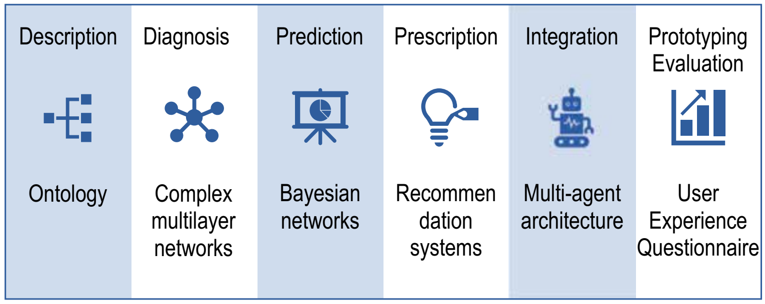
These approaches represent the connections of nodes in layers [22]. In these networks, connections can grow vertically or horizontally [22]. The

Figure 2. AL approaches.



Based on the studies by Martin and colleagues, Shute and Towle, and Vandewaetere and colleagues [13-15].

Figure 3. Methodology.



predictive model will be a Bayesian network. This network is a conditional probability graph [23]. The prescriptive model will be a recommender system. This system makes prescriptions based on user preferences [24]. To integrate these models, multi-agent architectures is used. This approach is standard for describing the integrated parts of a system [25-27]. The User Experience Questionnaire (UEQ) translated into Portuguese by Cota and colleagues [28] is used to analyze the students' perception of the AL proposed in the present study. This questionnaire analyzes three aspects. Attractiveness assesses whether users liked the proposal presented [29,30]. Hedonic quality analyzes non-task-related aspects [29,30]. Pragmatic quality assesses task-related aspects [29,30]. Nine postgraduate students of the integrated manufacturing systems discipline answer the UEQ in a pilot study.

Proposed Model

The proposed technological solution is an adaptive learning (AL) approach that aims to evaluate the performance of project-based learning (PBL) applied to technological disciplines. This solution is structured around five models to describe, diagnose, predict, and prescribe PBL characteristics and conditions that, when implemented, achieve the educational functions of PBL (Figure 4).

<u>Variables</u>

The characteristics are the problem, the assessment, the solution, the teacher, and the teams. The conditions are the implementation time, environment, format, and educational level.

The functions of PBL are to promote knowledge acquisition, problem-solving, and collaborative, constructive, self-directed, and contextualized learning.

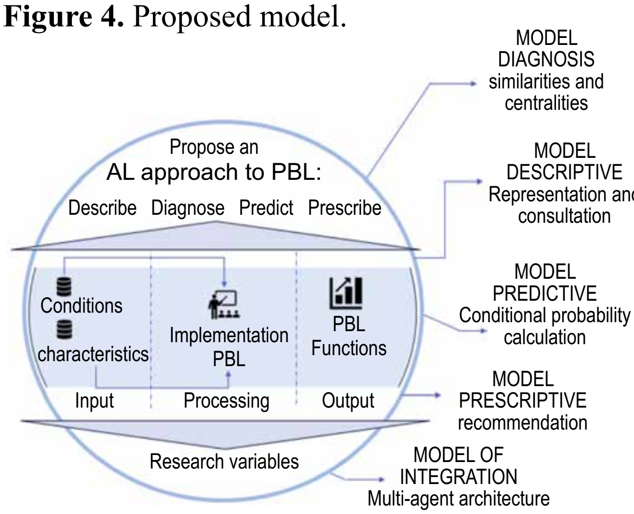
<u>Model functions</u>

The functions of the models are illustrated in Figure 5 and described in Table 1.

<u>Forms of Use</u>

The forms of use for teachers, students, researchers, industry, and educational institutions are detailed in Table 2 and 3.The problems and solutions developed can integrate teams from universities and industry. The models proposed in this study allow: consultations, metrics analysis, and recommendations regarding which teams are developing specific solutions.

Figure 4. Proposed model.



Expected Benefits

The expected benefits are described in Table 4.

User Guidelines

Six modules were developed that present the proposed models, development techniques, usage methods, and extension methodologies (Figure 6).

The present study also proposes guidelines for utilizing the models in conjunction with existing tools. These guidelines are available in http://educapes.capes.gov.br/handle/capes/983876. The proposed tool is licensed under the Creative Commons CC BY-NC 3.0 BR license. Therefore, non-commercial use, adaptation, and sharing of the proposed models are allowed.

Validation

The results show that the proposed approach was positively evaluated by the students in terms of attractiveness, hedonic quality, and pragmatic quality (Figure 7).

Figure 5. Proposed model.

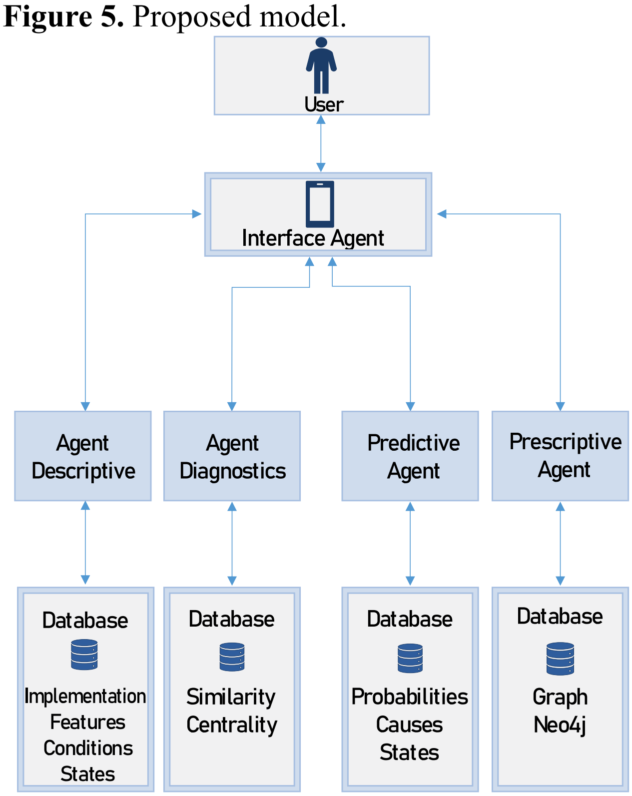


Table 1. Model functions.

Model Function	Description
Descriptive	The descriptive model aims to allow access and querying of the characteristics, conditions, and functional states of a PBL implementation.
Diagnostic	The diagnostic model proposes metrics to calculate centralities and similarities in the characteristics, conditions, and functional states of the PBL.
Predictive	The predictive model identifies the causal relationships related to the characteristics and conditions that lead a PBL implementation to achieve or not its educational functions.
Prescriptive	The prescriptive model aims to provide recommendations for characteristics and conditions to improve the PBL implementation results.
Integration	The integration model aims to establish how the descriptive, diagnostic, predictive, and prescriptive models are related.

As shown, students liked the proposed approach. The function-related and non-function-related aspects of the proposed models' approach were also positively evaluated.

Discussion

This study proposes novel AL models for PBL. These models advance the fourth wave of PBL research. Existing approaches focus on content and the learner model. The proposed approach considers broader aspects, such as the team, the problem, the solution, the assessment, and the teacher. This approach presents diverse functions for students, educational researchers, universities,

Table 2. Teaching and educational research.

User	Forms of Use
Researchers	Conduct research, train AI algorithms, and develop educational technologies using data generated by the proposed model.
Researchers	Conduct performance investigations of PBL implementations.
Researchers	Implement the integration of the technological solution's descriptive, diagnostic, predictive, and prescriptive models on a single platform.
Teachers	Plan the characteristics and conditions of a PBL implementation with process reuse, for example, projects, unsolved problems, and assessment models. Reuse has the potential to reduce the effort and time on planning PBL.
Teachers	Evaluate the quality of a PBL implementation by: (i) calculating similarities between implementations and states; (ii) analyzing the relationship between adaptations in implementations and the approach or distance from the achievement of PBL functions.
Teachers	Improve the quality of a PBL implementation through predictive analysis of the likely causes of the achievement or lack thereof of PBL functions in a specific implementation.
Teachers	Improve the quality of a PBL implementation through recommendations for: problems and students based on familiarity; problems based on area; existing solutions based on techniques; existing problems based on solutions; characteristics and conditions most likely to achieve collaborative learning, problem-solving, and knowledge acquisition.
Teachers	Manually integrate the descriptive, diagnostic, predictive, and prescriptive models of the technological solution with existing tools.
Educational managers	Develop initiatives and strategically direct resources.
Students	Identify teams for collaboration and solutions to existing problems to analyze innovation potential.
Students	Using metrics, assess the team's level of multidisciplinarity, familiarity with problems, and the scope of PBL learning functions.

graduate programs, the Ministry of Education, and industry.

Improved educational quality, increased collaboration on innovative projects, a database for AI training, and strategic educational decisions are some benefits of the proposed model.

The model validation showed positive student perception. However, this study was limited to experiments with a sample of students. Limitations and robustness related to study design are described in Table 5.

Future studies to analyze the perceptions of other potential users of the proposed model are recommended. Modules developed by the present study that guide the implementation of the proposed models in existing tools could aid these future studies. Manual integration of the models is a limitation of this study. Therefore, the development of a platform with a user-friendly interface is another recommendation for future studies. This research advances several AL challenges described in Table 6.

Table 3. Use in the integration between universities, government, and industry.

User	Forms of Use
Graduate Program	Considering that the problems are master's and doctoral projects, the problem data repository can help students identify: (i) advisors based on the projects; (ii) problems in topics of interest, familiarity, and ideal multidisciplinarity. This process can reduce research time and improve the indicators of postgraduate programs in Brazil.
Industry and Corporate Environment	Considering that projects developed in a corporate environment are problems that generate commercialized solutions, identifying development conditions (such as time, format, implementation environment) and characteristics (such as team, problem-solution, supervisors' role) that lead the team to develop the project with self-direction, collaboration, constructiveness, and a problem solved within a specified timeframe impacts the success of this organization. Identifying the most appropriate teams for developing specific projects more quickly is another benefit for the corporate environment.
Higher Education Institution	An overview of PBL practices implemented at the institution identifies: (i) the projects and problems solved; (ii) the teams developing the solutions; (iii) the integration of teams within the institution; (iv) the implementations that achieve PBL functions. This process enables the educational institution to have a broad view of the projects developed for direct strategic resources.
Government represented by the Ministry of Education	The Ministry of Education proposes new curricular guidelines for engineering programs and other technologically-based programs. Therefore, identifying the characteristics and conditions that bring PBL implementations closer to achieving their intended purpose allows for: (i) identifying best practices; (ii) assisting in the improvement of these guidelines; and (iii) analyzing the results of the proposed guidelines.

Table 4. Expected benefits of the project.

ID	Benefits of the Project
1	Reduced effort and time required by teachers.
2	Increased collaboration within the educational institution.
3	Increased innovative solutions designed in educational environments.
4	Performance analysis of PBL implementations.
5	Access to a database of educational needs and processes.
6	Improving educational quality.
7	Strategic development of research, initiatives, educational technologies, and AI algorithm training.

Figure 6. User guidelines.

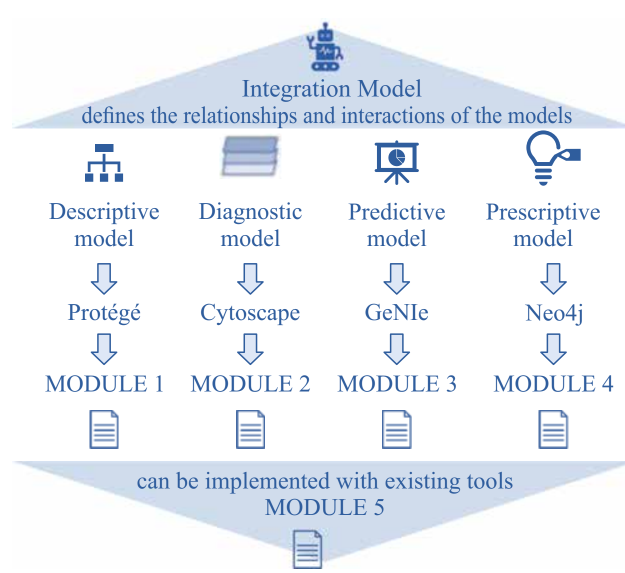


Figure 7. Students' perception of the proposed models.

Conclusion

The present study developed an AL approach to PBL. This innovative approach have potential: (i) reduced teacher effort in PBL planning; (ii) increased collaboration educational institution and industry; (iii) increased innovative solutions designed in educational environments; (iv) performance analysis of PBL implementations; (v) access to a database for improving educational quality, strategic development of research, initiatives, educational technologies, and AI algorithm training; (vi) interoperable with various technologies, such as ontology editor software, network analysis, knowledge graph analysis, and Bayesian network analysis. The functions of the proposed model were positively evaluated for students.

Table 5. Limitations and robustness.

ID	Limitations and robustness
1	No reducing education to measurable outputs and no restricting it to corporate efficiency: The approach accommodates qualitative and quantitative data from descriptive and diagnostic models. This combination enriches the possibilities for understanding PBL and does not restrict education to measurable outcomes. The diverse uses for research, teaching, management, and organizational strategies demonstrate that the proposed approach considers critical analysis and is not limited to corporate efficiency.
2	Validation: The UEQ technique is not intended to assess educational quality. It only indicates evidence that potential users are interested in using it. The adaptability of PBL during implementation challenges evaluations using case-control designs. The diagnostic model's metrics can be used to measure the quality of the PBL implementations and analyze whether improvements in PBL functions are being achieved. Therefore, the proposed approach helps improve educational quality.

The study's limitations include: (i) validation related to the user experience with students; (ii) implementation with manual data integration using existing platforms. It is recommended that future studies: (i) implement the technological solution to integrate universities and industry; (ii) develop a web implementation of the solution with user training and support; (iii) use other validation techniques with a larger sample of students.

Acknowledgement

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Table 6. Advances.

ID	Advances
1	Epistemological conflicts: Studies indicate epistemological weaknesses in AL related to reducing the complexity of education by providing rules for action [31]. For Ross [31], AL should suggest possible actions and an understanding of possibilities. In line with this author's recommendations and unlike existing approaches, this study proposes recommendations for the characteristics and conditions of PBL for critical analysis by teachers and scientific research. The proposed approach is a digital method, and understanding epistemological limits is a challenge in multidisciplinary areas of science [32].
2	The proposed approach reconciles algorithmic personalization (AL) with the collective and open nature of PBL in: (i) scalability—the proposed approach is open to collaborations; (ii) variables—collaborative learning, the team, and interactions are model variables; (iii) use—access to data from the prescriptive model allows solutions to be developed more collaboratively by allowing students to contribute to project solutions from other disciplines, courses, and institutions.
3	How can we avoid this from reducing PBL to a mechanistic process, emptying its critical and multidisciplinary function? How to prevent students from perpetuating disciplinary bubbles? The proposed approach has the following characteristics: (i) it does not reduce PBL to a mechanistic process—the intention is to provide data for investigations into the complex interaction of PBL components; (ii) it considers criticism—teachers and students consult on aspects of PBL, critically analyze it, and choose how they will plan the PBL; (iii) it considers multidisciplinarity—problems can be modeled with a level of multidisciplinarity and familiarity defined by the teacher. With the help of the proposed approach, the teacher can prevent students from restricting themselves to their areas of expertise.
4	AL can reduce flexibility by standardizing ideal responses with limiting causality modeling by Bayesian networks, which stand out for their transparency [33]. AL needs transparency about algorithmic bias: The proposed approach does not indicate ideal responses, but rather possibilities. Access to implementation variability tends to increase the flexibility of PBL. The proposed Bayesian network does not recommend learning paths, but rather indicates probable causes of problems, which must be critically analyzed by the teacher and investigated by researchers.
5	No restriction of the predetermined paths and considering autonomous learning: There are no recommendations for predetermined paths in the proposed AL. Therefore, the system recommends, and the student has the autonomy to select problems and develop solutions different from those registered.

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Development of a Permanent Bicycle Chain Maintenance and Cleaning Device

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This article aims to develop an innovative solution for the dirt accumulation challenges faced by long-distance cyclists in maintaining their bicycle chains clean and functional for longer periods. The methodology employed involved a detailed analysis of existing products on the market, identifying their strengths and weaknesses. This comparative analysis served as the basis for the development of an optimized product capable of withstanding adverse weather conditions, ensuring continuous lubrication, and preventing the accumulation of dirt. The results achieved demonstrate the feasibility of a solution that extends the lifespan of the chain, reduces the need for maintenance, and significantly improves the performance and safety of cyclists, allowing them to focus exclusively on their cycling experience.
Keywords: Lubrification. Transmission. Bicycle. Chain. Performance. Maintenance.

The bicycle chain is a critical power transmission component whose performance is compromised by particulate accumulation and insufficient lubrication, leading to accelerated wear, reduced efficiency, and even safety risks as pointed by REI [1]. This issue is particularly acute for Mountain Bikes, which are not only the market's most popular category, sold by over 90% of stores in Brazil, according to Aliança Bike, 2024 [2], but are also the most affected by contamination in off-road environments (e.g., Figure 1), where indispensable maintenance procedures are laborious and impractical.

The sector's financial health, with an average 2023 gross revenue of R$500,000 per shop in Brazil [2], underscores the commercial opportunity for innovation. While various solutions exist, a permanent, integrated device providing efficient, autonomous maintenance has not been effectively realized. The primary objective of this project is to address this challenge by developing a product that ensures sustained chain function, thereby enhancing reliability and allowing cyclists to focus entirely on performance. The realization of this concept follows a structured product development methodology, which this article document from the initial informational design through to the final project specifications.

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Materials and Methods

This methodology applied to this project was the Product Development Process (PDP) which is based on the issue observation, going through 17 steps of investigation, raising customer needs, identifying product requirements up to concept development and final product definition.

Throughout the development process, various strategic tool and concepts were employed. This project started by identifying an issue, which was the short durability of bicycle chains that are recurrently submitted to off-road trails (Figure 1). This issue was raised during a brainstorm session from the team members based on personal knowledge and experience, as some of the members have track riding experience.

The next step was an extensive bibliographic review through e-commerce pages to identify the currently available solutions, how they function and identifying improvement opportunities.

Once the opportunity was identified and the competitors were mapped, the team came up with a questionnaire "Problemas de sujidade no sistema de transmissão de bicicletas em trilha"

Figure 1. Dirty bicycle after an off-road ride.

Source: Transbike [3].

[4] on Microsoft Forms to deepen the knowledge of the real customer needs and pain points. The questionnaire was shared to cycling groups and received a 32 responses, that greatly contributed to the development.

The questionnaire was used to map the client's needs, by applying Global Functions and Functional Synthesis tools, which has helped in translating the responses into functional requirements which were applied on the next phases.

The functional requirements were input onto the QFD, TRIZ and Morphological Matrix, which resulted of robustness of 5 concepts, leading to the final Solution selection.

The PDP methodology used on this process has been developed and described by authors Back and colleagues (2008) [5], Baxter (1998) [6] and Rozenfeld (2006) [7].

Results and Discussion

Interfaces

The intricate interplay between the cyclist, the bicycle, the external environment (trails, forest, mud, etc.), creates a complex web of factors that directly influence the performance and durability of the drivetrain; accumulated dirt can compromise pedaling efficiency, increase wear on parts, generate annoying noises, and, in extreme cases, lead to mechanical failures that interrupt the cyclist's experience. In this context, understanding the nuances of this relationship (how trail type, weather conditions, cyclist maintenance habits, and component quality combine to determine drivetrain dirtiness) is crucial for mitigating negative effects and ensuring a smoother, more efficient, and long-lasting ride, this scenario is addressed by a system-problem diagram (Figure 2).

Benchmark

Prior to conceptualizing our product, a comprehensive benchmark study was undertaken. This systematic comparison of existing market solutions aimed to identify their operational mechanisms, pinpoint their strengths and weaknesses, and ultimately uncover opportunities for competitive differentiation. The research revealed that while current offerings span categories such as chain cleaners (special soaps and degreasers), active cleaning equipment (brushes and microfiber yarn), semi-automatic cleaners (attachable devices with rotational mechanisms), and chain covers, none adequately address the comprehensive needs outlined for our proposed solution, thereby highlighting a clear market gap (Figure 3).

Besides different products aimed to be used on the traditional bicycle transmission system made of a chain and sprockets, the study uncovered other unconventional transmission systems like a belt driven drivetrain and driveshaft connected system that promise to deliver a more robust system that don't require active cleaning and lubrication of the system.

Customer Needs

Data from the questionnaire [4], combined with market research on similar products allowed for the identification of key customer needs and a comprehensive understanding of consumer expectations. These needs were subsequently translated into a concrete set of design requirements.

The requirements serve the critical function of converting abstract customer needs into a precise,

Figure 2. System-problem interface diagram.

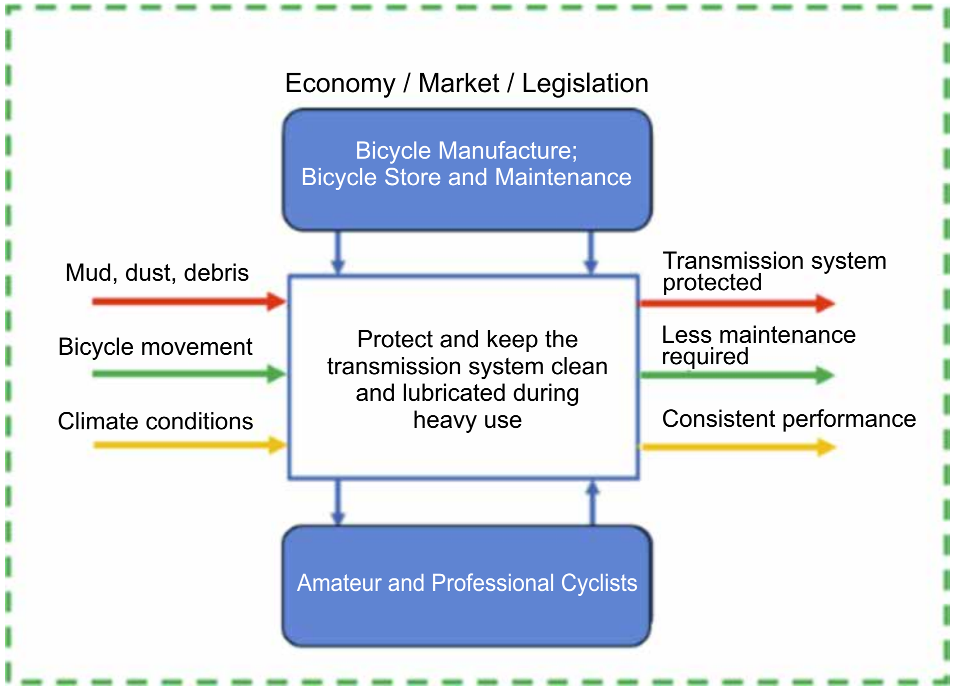


Figure 3. Identified competitors.

1. Chain cleaner [8] 2. Attachable device [9]. 3.Brushes [10] 4. Cover [11].

technical language with measurable characteristics. This conversion establishes an objective framework to guide and validate all subsequent design efforts. These are subsequentially used as the starting point of the QFD (Quality Function Deployment) process.

QFD

The result of applying the QFD method resulted in 10 needs identified for 3 specific types of customers, in which each one received a different weight. To the manufacturer it was given 10% weight, to the sales rep. 30% and to the end user 60%. Based on the results obtained from the questionnaire [3], a grade was attributed to each of the identified needs. That information collected resulted in a total of 13 requirements being translated. The end results of the methodology we observed in Table 1 and Table 2, which brings the product's lifespan increase as the highest scoring requirement.

TRIZ

Once the customer needs were identified, translated to requirements and systematically analyzed and scored through the use of QFD. Translated as "Theory of Inventive Problem Solving" it is a strong methodology that helps foster innovation and solve complex technical

Table 1. Correlation between needs and project requirements.

#	Client	Need	Client's Weights	Client's Grades	Production Cost	Number of Components	Standardized Components	Product's Volume	Efficiency Loss	Selling Price	Installation time	Installation Special Tools	Weight	Time between maintenances	Maintenance time	Cleaning time	Lifespan
					#	#	#	mm³	%	R$	min	#	g	weeks	min	min	km
					↓	↓	↑	↓	↓	↓	↓	↓	↓	↑	↓	↓	↑
A	Manufacturer	Low cost of production	10%	9	8	4	4	2	0	8	0	0	2	0	0	0	4
B	Seller / Market Place	Install needs to be done without user special expertise	30%	9	0	2	2	0	0	4	8	8	0	0	2	2	0
C	Consumer / User	Product will be used with low need of special tool	60%	3	0	0	0	0	0	4	4	8	0	0	4	0	0
D		Product needs to be small	60%	1	2	0	0	8	0	2	0	0	4	0	0	2	0
E		Product is light so it doesn't bother the cyclist on a ride	60%	1	2	0	0	4	0	2	0	0	8	0	0	0	2
F		Resistant to continuous use with low maintenance	60%	9	8	2	0	0	4	4	0	0	2	8	0	0	8
G		Low purchase price	60%	6	8	4	4	2	0	8	0	0	2	0	0	0	4
H		Low to no maintenance	60%	6	0	4	0	0	4	4	0	0	0	8	8	4	8
I		Product needs to maintain itself clean	60%	9	0	0	0	0	8	0	0	0	0	4	2	8	8
J		Product will maintain cyclist's performance	60%	1	0	0	0	0	8	0	0	0	2	8	2	0	8
		Requirements' Priority Ranking		82	82	49	23	16	84	92	29	36	28	98	53	64	139

Table 2. Roof of the house of quality matrix.

Legend:

2	Very Positive Relation
1	Positive Relation
0	Neutral
-1	Negative Relation
-2	Very Negative Relation

	Qty of Components	Standardized Components	Product's Volume	Efficiency Loss	Selling Price	Installation time	Installation Special Tools	Weight	Time between maintenance	Maintenance time	Cleaning time	Lifespan
Lifespan												
Cleaning time												0
Maintenance time											2	0
Time between maintenance										0	0	2
Weight									0	0	0	0
Installation Special Tools								0	0	1	0	0
Installation time							2	0	0	1	0	0
Selling Price						1	1	-1	-2	0	0	-2
Efficiency Loss					-1	0	0	0	2	0	0	1
Product's Volume				0	-1	0	0	1	0	0	0	0
Standardized Components			-1	0	2	0	2	-1	0	0	0	0
Qty of Components		0	1	0	1	2	1	1	0	1	1	0
Production Cost	0	0	1	0	-2	0	0	2	1	0	0	1

problems by using universal patterns of innovation to identify and resolve contradiction inherent in design requirements. The four inventive principles resulted from the methodology (Table 3) helped in drafting what would be the first concepts of the proposed solution and would be the base of the Morphological Matrix.

Morphological Matrix

With the previous steps completed and rough drafts generated a morphological matrix was started to assist in defining the functions that each concept would address in order to meet the solution proposed by the initial problem.

During this phase, five alternative solutions emerged (Table 4) that cross-combined eight elemental functions to address the bike drivetrain's three core functions: protection, lubrication, and cleaning.

Concept Selection

The concepts were evaluated with the Pugh Matrix, in which customer needs and their respective weights (derived from the QFD) served as the decision criteria. "0" indicated parity with the datum, "+1" superior fulfilment and "–1" inferior fulfilment.

The concepts idealized were: C1: PTFE-coated chain plus curved-tooth scraper; C2: PTFE-coated chain plus super-hydrophobic spray; C3: Full protective sleeve with passive wax dripper; C4: Handle-bar-actuated dripper with twin brushes; C5: Rear-derailleur housing filled with bees-/carnauba-wax.

Two progressive screening rounds comparing the concept with other market products and were made. First against the cover (Table 5), and finally head-to-head (Table 6), ranked the candidates and revealed the most promising ideas according to the attendance of costumer needs.

Tables 5 show that Concept 2 consistently outperformed the datum and its peers, obtaining net scores of +16.2.

Table 6 reveals that, when the concepts are compared exclusively among themselves, Concept 5 achieves the highest overall score, closely followed by Concept 2. In contrast, Concepts 1, 3 and 4 deliver onlymarginal or even negative benefits: they add excessive mass, demand specialized installation tools, or drive the product cost beyond an acceptable level.

A hybrid solution, hereafter Concept 6 (e.g., Figure 4) was therefore synthesized by merging the two front-runners: the low-friction, factory-impregnated PTFE chain from Concept 2 and the compact wax-reservoir envelope from Concept 5. This combination retains the self-cleaning advantage of the hydrophobic coating while adding a continuous, solid-phase lubricant that re-coats the rollers as they pass through the felt applicator. So the Concept 6 fulfils all three key functions identified as essential to the product.

Conclusion

This work introduces a compact module that simultaneously protects, lubricates, and cleans bicycle drivetrains by pairing a low-friction, PTFE-treated chain with a solid-wax reservoir and felt applicator. The concept emerged from a structured design route that blended QFD priorities, TRIZ contradiction mapping, morphological recombination, and multi-stage Pugh screening, ensuring that customer value, technical feasibility, and cost discipline were addressed in parallel.

In summary, the proposed drivetrain module advances bicycle reliability and sustainability while remaining sensitive to cost and ease-of-use. Widespread adoption could lower maintenance burdens for riders, minimize lubricant waste and set a new benchmark for eco-efficient cycling components. Achieving full market readiness will require extended field testing, fine-tuning of material formulations, and collaboration with supply-chain partners to establish circular end-of-life pathways. Nevertheless, the proposed module stands poised to raise performance standards across the cycling sector.

Table 3. Inventive principles indicated by the TRIZ method.

Contradiction	Improving Parameter	Worsening Parameter	Inventive Principle
Lifespan *vs* Selling Price	16. Durability of nonmoving object	32. Ease of manufacture	10. Preliminary action 35. Parameter changes
Lifespan *vs* Selling Price	15. Durability of moving object	32. Ease of manufacture	27. Cheap short-living objects 1. Segmentation 4. Asymmetry
Standardized Components *vs* Weight	36. Device complexity	1. Weight of moving object	26. Copying 30. Flexible shells and thin films 34. Discarding and recovering 36. Phase transitions
Selling Price *vs* Efficiency Loss	21. Power	32. Ease of manufacture	10. Preliminary action 26. Copying 34. Discarding and recovering

Table 4. Morphological matrix.

Function N1		Function N2	S1	S2	S3	S4	S5	S6
F1	Install Product to bicycle	Clean Transmission	Brush	Nylon “Floss”	Water Jet	Cloth	Compressed air	Grease remover
F2		Fix product to system	Screws	Nylon Clamps / Hellermann tie	Snap Fit	Adhesive	Metallic Clamp	Weld
F3		Regulate / Adjust product	Manual	With tools				
F4	Check functional ity	Ensure functionality	Visual	Level	Engagement	Moving the system	Luminous	Audible
F5	Protect the transmiss ion system	Ensure system protection	Cover	Chemical (hydrophobic)				
F6		Ensure lubrication	PTFE	Manual application of liquid lube	Semi-automatized	Automatized liquid lubrication	Passive liquid lubrication (immersion)	Solid Lubrication (grease / wax)
F7		Ensure system cleanliness	Cover	Scraper	Brush	Centrifugal Force		
F8	Verify system integrity	Ensure system integrity	Visual	Level	Engagement	Moving the system	Luminous	Audible

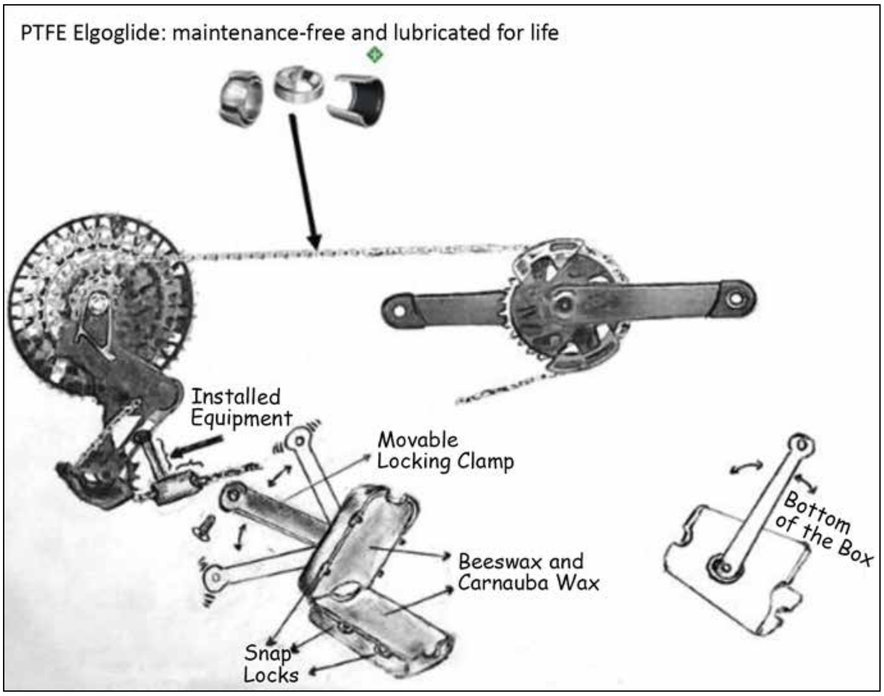
Table 5. Generated concepts *vs* protective cover.

#	Client	Need	Grades	Weights	I	II	III	IV	V
A	Manufacturer	Low cost of production	9	10%	-1	-1	-1	-1	-1
B	Seller / Market Place	Install needs to be done without user special expertise	9	30%	0	1	0	0	0
C		Product will be used with low to no need of special tool	3	60%	0	1	0	1	0
D		Product needs to be small	1	60%	1	1	0	1	0
E		Product is light so it doesn't bother the cyclist on a track ride	1	60%	1	1	0	1	0
F	Consumer / User	Resistant to continuous use with low maintenance needs	9	60%	1	1	1	1	1
G		Low purchase price	6	60%	-1	-1	-1	-1	-1
H		Low to no maintenance	6	60%	1	1	1	1	1
I		Product needs to maintain itself clean	9	60%	1	1	1	1	1
J		Product will maintain cyclist's performance	1	60%	1	1	1	1	1
				Total	11.7	**16.2**	10.5	**13.5**	10.5

Table 6. Generated concepts *vs* concept 2.

#	Client	Need	Grades	Weights	I	II	III	IV	V
A	Manufacturer	Low cost of production	9	10%	-1		1	1	1
B	Seller / Market Place	Install needs to be done without user special expertise	9	30%	-1		-1	-1	-1
C		Product will be used with low to no need of special tool	3	60%	-1		-1	-1	0
D		Product needs to be small	1	60%	-1		-1	-1	-1
E		Product is light so it doesn't bother the cyclist on a track ride	1	60%	-1		-1	-1	-1
F	Consumer / User	Resistant to continuous use with low maintenance needs	9	60%	0		-1	-1	-1
G		Low purchase price	6	60%	-1		1	1	1
H		Low to no maintenance	6	60%	0		0	0	0
I		Product needs to maintain itself clean	9	60%	1		0	0	1
J		Product will maintain cyclist's performance	1	60%	0		0	0	0
				Total	-4.8	0	-6.6	-6.6	**0.6**

Figure 4. Concept 6.



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Advancing Circularity in Additive Manufacturing: Life Cycle Assessment of Post-Consumer PA12 Recycling

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Additive Manufacturing (AM) has emerged as a transformative technology in industrial production, enabling the fabrication of complex geometries with reduced material waste compared to conventional methods. Among its techniques, Powder Bed Fusion (PBF) is widely applied to polymeric materials such as polyamide 12 (PA12), producing durable components that eventually reach end-of-life. The growing volume of discarded AM parts highlights the need for sustainable end-of-life strategies, with mechanical recycling offering a promising pathway to close material loops within a circular economy. This study evaluates the environmental performance of post-consumer PA12 recycling from prototypes and parts manufactured via PBF using the HP Multi Jet Fusion 5210 printer. The assessment followed ISO 14040 and 14044 guidelines, adopting a cradle-to-gate boundary and a functional unit of 1 kg of recycled PA12 pellets (PA12r). Data were based on primary measurements at SENAI/CIMATEC's facilities, complemented by secondary datasets from Ecoinvent 3.10.1. The product system comprised five stages: Cascalheira Milling, Cimatec Park Milling, Manual Washing, Drying, and Extrusion/Pelletizing. Life Cycle Impact Assessment (LCIA) results, focused on Global Warming Potential (GWP100, IPCC 2021), showed PA12r achieved a 10% carbon footprint reduction compared to virgin PA12. Drying was the most impactful stage in total emissions, while Extrusion/Pelletizing had the highest hourly rates, underscoring their critical roles in optimization. Electricity consumption was the dominant contributor, influenced by equipment demand and Brazil's energy mix. Findings show the technical and environmental potential of scaling PA12 recycling for additive and conventional manufacturing, while addressing a literature gap and supporting recycling integration in AM supply chains to boost circularity and reduce impacts.

Keywords: 3D Printing. PBF. Carbon Footprint. Circular Economy.

Additive Manufacturing (AM) has gained prominence in the industrial landscape due to its ability to revolutionize the design and production of components, offering flexibility for manufacturing complex geometries with greater material efficiency. Unlike conventional processes, which generally involve machining or molding by removing material, AM builds parts layer by layer, reducing waste and enabling greater design freedom. Among the various AM techniques, Powder Bed Fusion (PBF) stands out for using a powder bed selectively fused by thermal energy, as defined by ASTM 52900:2021. This technology is widely used with polymeric materials such as polyamides, producing durable products that eventually reach the end of their useful life, requiring appropriate disposal solutions, such as recycling, to re-enter the production chain. These processes must be evaluated in terms of environmental aspects and impacts to ensure environmental gains with the technology [1].

In this context, Life Cycle Assessment (LCA) emerges as an essential tool for quantifying the environmental impacts of products and processes, enabling the identification of improvement opportunities and comparison between different technologies. One important environmental impact related to climate change is the Global Warming Potential (GWP 100), which, according to the updated IPCC methodology (2021), measures greenhouse gas emissions throughout the product's

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life cycle. Applying LCA is fundamental to understanding the real environmental benefits of recycling strategies compared to producing virgin material [2].

This study aimed to assess the environmental impacts of recycling PA12 parts and prototypes produced using Powder Bed Fusion (PBF) technology in the HP Multi Jet Fusion (MJF) 5210 printer. Using the Life Cycle Assessment (LCA) methodology, with emphasis on the carbon footprint, the study sought to quantify the environmental benefits of post-consumer recycling of these materials. The results aim to contribute to developing circular economy strategies in additive manufacturing.

Materials and Methods

Recycled PA12 Pellets

Pellets are small spheres or cylinders of granulated plastic, typically 2 to 5 mm in diameter, used as raw material in plastic processing operations. The LCA target in this study is the process of manufacturing PA12 pellets from the recycling of post-use prototypes and parts produced by 3D printing on the HP MJF 5210, at the Additive Manufacturing Bureau of Cimatec Park. The growing volume of printed and discarded parts demanded a sustainable management solution, which motivated the development of this research.

Life Cycle Assessment (LCA) [3,4]

Product System

The product system considered in the LCA consists of five main processes, four powered by electricity: Cascalheira Milling (industrial mill Mecanofar 230); Cimatec Park Milling (pilot-scale mill Mecanofar 160); Manual Washing; Drying (bench oven MedClav Mod1 11L); and Extrusion/Pelletizing (bench extruder and mini-granulator AxPlásticos).

The process began with Cascalheira Milling, the first fragmentation stage, in which prototypes were broken into coarse PA12 flakes. Next, Cimatec Park Milling further reduced flake size to less than 4.75 mm. After milling, the material underwent washing to remove impurities such as oils, greases, dust, and residual virgin PA12 powder adhered to internal surfaces of hollow parts, using neutral detergent and running water.

Drying followed, with flakes placed in an oven in two stages: first, for eight hours at 70 °C, then homogenized and dried again for 16 hours at 100 °C to ensure adequate moisture reduction. Finally, the fully dried material underwent extrusion and pelletizing. In this stage, PA12 flakes were transformed into a filament of variable diameter and immediately granulated, resulting in PA12r pellets ready for reuse. Figure 1 presents the flowchart containing the steps.

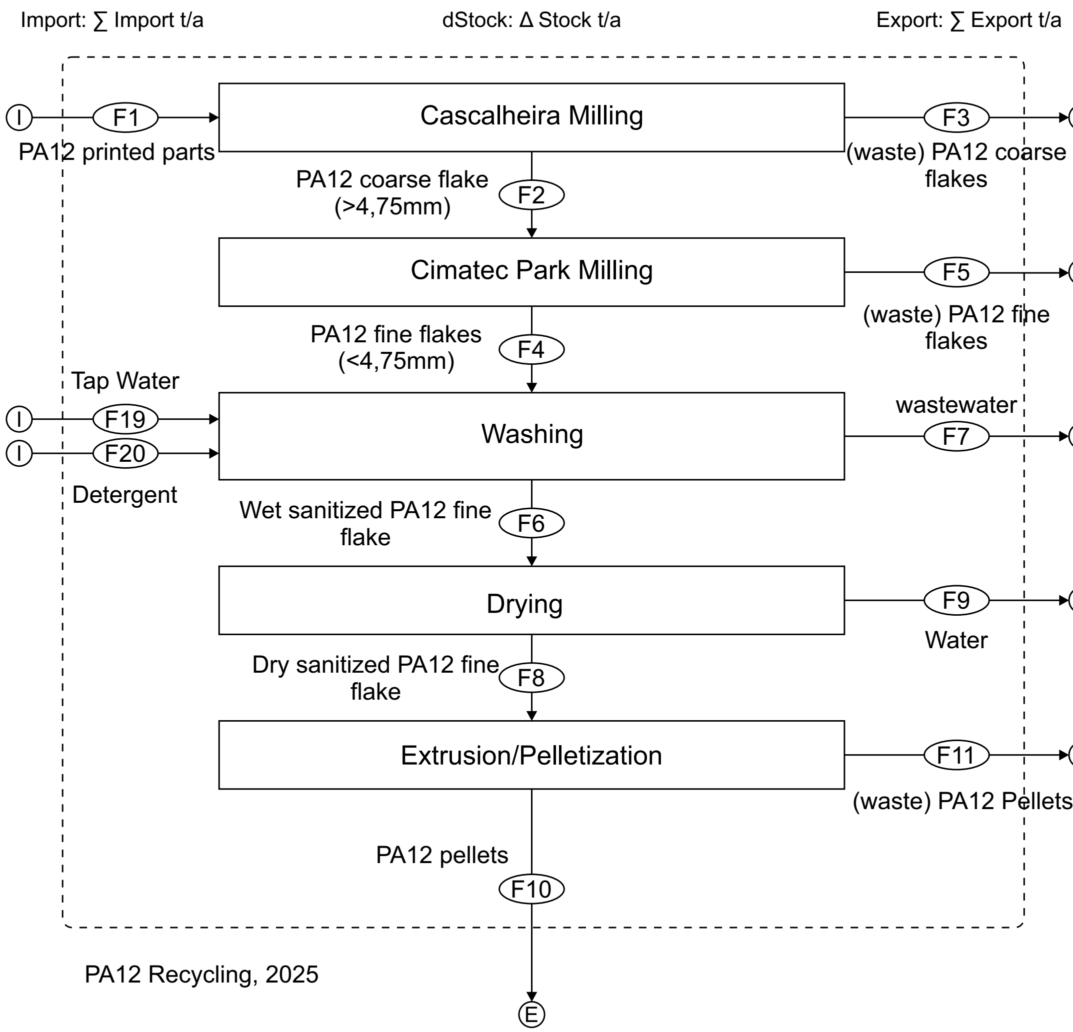
Software and Database

The LCA was carried out using OpenLCA software version 2.4.0 and the Ecoinvent 3.10.1 Cut-off database. Primary data were obtained through direct measurements during recycling stages. Equipment energy consumption parameters were estimated from manufacturer technical specifications and machine operating times for each step. Secondary data from Ecoinvent were also used and adjusted to better represent the real process conditions. The data inputs used for the production of 1UF of PA12r pellets were summarized in the inventory presented in Table 1.

Data Quality and Uncertainty Propagation

Uncertainty quantification was performed using the Pedigree Matrix, as proposed by Weidema and Wesnæs (1996). Uncertainty propagation was estimated via Monte Carlo simulation with 5,000 iterations and a 90% confidence interval. This combined approach strengthened the representativeness of the data and contributed to the robustness and reliability of the results [5].

Figure 1. Product system related to the mechanical recycling process of prototypes and parts printed in PA12.



Results and Discussion

Life Cycle Impact Assessment (LCIA)

For comparison purposes, the carbon footprint of virgin PA12 for the same functional unit was obtained from the Plastics Database [6]. The first LCIA analysis compared the environmental impact of producing virgin PA12 granules and PA12r pellets.

Results showed that PA12r pellets presented environmental advantages over virgin PA12. The recycling process developed at SENAI/CIMATEC recorded emissions of 5.19 kg CO_2 eq/kg of PA12r, representing a reduction of approximately 10% in carbon footprint (Figure 2).

The LCIA results, referring to the different stages of the PA12 recycling process, can be observed in Figure 3. The interpretation of the data showed a significant variation in environmental impacts throughout the process, with emphasis on the Drying and Extrusion/Pelletizing stages for presenting considerably higher environmental loads when compared to the Milling and Washing stages.

A comparative analysis of the process stages revealed significant differences in environmental impacts. The drying stage showed the highest greenhouse gas emissions, totaling 3,133 kg CO_2e, which corresponds to 60.3% of the total emissions from the recycling process (5,195 kg CO_2e). In

Table 1. Inputs and outputs for the production of 1kg of PA12r pellets.

Item	Intermediate and elementary flows in Ecoinvent v3.10.1	Required amount	Unit
Inputs			
PA12 printed parts	-	1.10	kg
Electricity	market group for electricity, low voltage | electricity, low voltage | Cutoff, U - BR	71.89	MJ
Detergent	market for non-ionic surfactant | non-ionic surfactant | Cutoff, U - GLO	0.04	kg
Water	market for tap water | tap water | Cutoff, U - BR	12.38	kg
Outputs			
PA12 pellets	-	1.00	kg
Plastic Waste	treatment of waste plastic, consumer electronics, sanitary landfill, wet infiltration class (500mm) | waste plastic, consumer electronics | Cutoff, U - GLO	0.14	kg
Wastewater	market for wastewater, unpolluted | wastewater, unpolluted | Cutoff, U - RoW	0.01	m^3

Figure 2. Climate Change Impact Category LCIA for the production of recycled granulated plastic, Evonik granulated PA12, and recycled PA12 pellets at SENAI/CIMATEC.

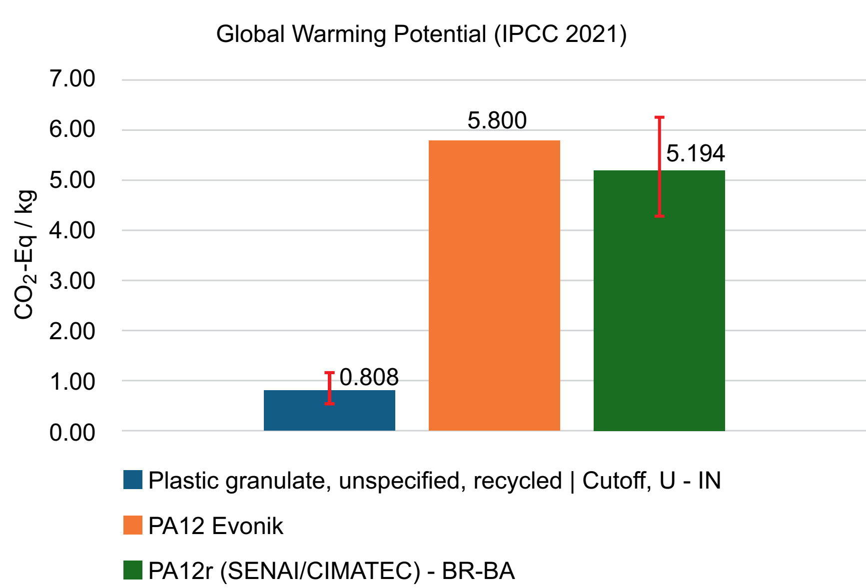
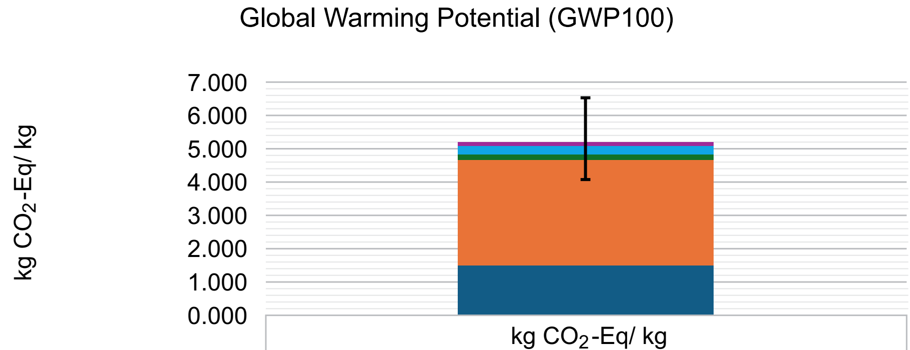


Figure 3. Global Warming Potential (GWP100) for the production of 1 kg of recycled pellets.



	kg CO_2-Eq/ kg
Cascalheira Milling	0.076
Cimatec Park Milling	0.272
Washing	0.187
Drying	3.133
Extrusion/ Pelletizing	1.525

comparison, the extrusion/pelletization stage contributed 1,525 kg CO_2e, representing 29.4% of total emissions. These results demonstrate that drying is the most critical stage in terms of carbon emissions within the recycling process.

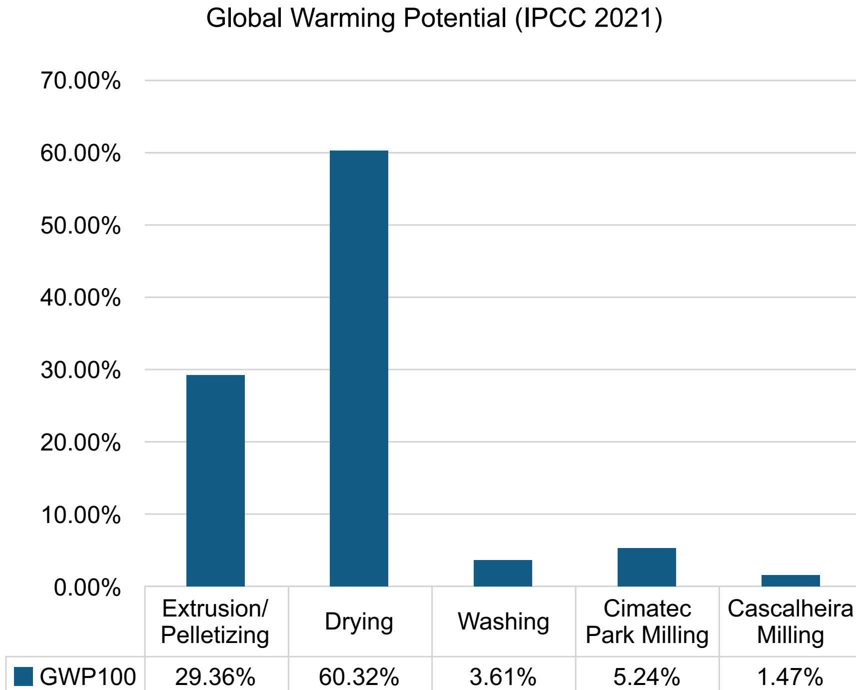
In contrast, the Cascalheira Milling stage showed a modest contribution to the total environmental impact, representing only about 1.5% of the global ecological load of the process. For a comprehensive understanding of the distribution of impacts, Figure 4 presents the relative performance of each stage for the assessed impact categories. It is noteworthy that the results presented correspond to an experiment that was developed mostly on a bench scale. Only the Cascalheira Milling stage used industrial-scale equipment.

The highest CO_2-Eq/kg values appeared in the Drying stage; however, when analyzing the operating time, it is observed that the Extrusion/ Pelletizing stage presented more significant emission results. CO_2 emissions were significantly higher in the last stage of the process, reaching 0.46 kg CO_2-Eq per hour compared to 0.13 kg CO_2-Eq per hour in Drying—a difference of about 3.5 times greater. Drying showed the highest total impacts due to the prolonged oven time, but Extrusion/ Pelletizing proved to be the most demanding process in operational terms.

The carbon footprint identified in this LCA arises mainly from electricity consumption, considering both direct use by equipment and the predominantly hydroelectric Brazilian energy matrix. The current project allows adjustments to optimize results, either through scaling up to an industrial level or using renewable energy sources.

All values presented here were calculated based on the Cut-off approach, which disregards the environmental impact associated with the input of recycled material, assuming that this impact has already been accounted for in the original part's life cycle. On the other hand, the Product Environmental Footprint (PEF) methodology makes it possible to allocate burdens and credits between the supplier and the user of recycled materials through the Circular Footprint Formula (CFF), which integrates aspects related to material, energy, and disposal. The CFF ensures that both the impacts associated with the recycled content present in the product (R1) and its recyclability at the end of its useful life (R2) are considered, avoiding double counting and providing a more accurate environmental assessment. Although this methodology has not yet been implemented in LCA software, it is likely to be incorporated in the near future, making the allocation process of impacts in product life cycles more aligned with the reality of recycling and recyclability [7].

Figure 4. Relative carbon footprint results for each stage of PA12 prototype recycling.



It is important to note that the literature review conducted for this work revealed the absence of specific studies on polymer recycling from additive manufacturing. This finding shows that research related to the circularity of parts and prototypes manufactured by this technology, as well as their environmental impacts, is still at an early stage, representing a relevant scientific gap in the area.

Conclusion

This study analyzed the life cycle of recycling 3D-printed PA12 parts and prototypes using powder bed fusion on an HP Multi Jet Fusion printer. The chosen impact category was Climate Change – Global Warming Potential (GWP100) (IPCC 2021). The system boundary followed a cradle-to-gate approach, covering raw material extraction to production, before product distribution.

The proposal to produce PA12r pellets was supported by the possibility of using the recycled material in various manufacturing methods (additive and conventional), ease of production with available equipment, and lower operational complexity compared to producing 3D printing filaments.

The Life Cycle Assessment (LCA) results revealed significant findings about the PA12 recycling process, demonstrating environmental advantages compared to conventional production. It was found that the bench-scale process for producing recycled PA12 pellets showed superior environmental performance to virgin granulated PA12 production, particularly regarding carbon footprint. This result suggests that scaling up the process to industrial levels could generate substantially lower environmental impacts, reinforcing its sustainable potential.

The analysis identified the Drying stage as the most critical phase of the recycling process, followed by the Extrusion/Pelletization stage. Quantitative data showed significant differences, with values slightly exceeding 50% between these stages. Specifically, Drying emerged as the phase with the highest total impacts, mainly due to the extended operation time of the oven. On the other hand, Extrusion/Pelletization proved to be the most operationally demanding process, requiring greater attention for potential efficiency improvements.

From an environmental perspective, recycling PA12 prototypes is particularly relevant as it provides proper material destination, avoiding negative environmental impacts. Instead of being disposed of in landfills, the waste is transformed into recycled pellets, which re-enter the production cycle as secondary raw material. This mechanism not only prevents waste generation but also promotes material circularity, aligning with circular economy principles and contributing to more sustainable production systems.

Thus, despite process scale limitations, recycling PA12 parts and prototypes from additive manufacturing shows great potential for developing products using PA12r pellets.

Acknowledgement

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A Proposal for Renewable Energy Viability and Environmental Conservation in the Caatinga: Challenges and Opportunities

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The need to preserve the Caatinga, characterized by a semiarid climate, high temperatures and low humidity with long periods of drought, while considering methods that could utilize these characteristics to minimize their adverse effects, poses a challenge. Despite this need, climate change has sparked significant global concern through the reduction of CO_2 emissions. Given this scenario, clean energy generation presents an important alternative to overcome climate challenges. This study seeks to bridge these two needs by sharing resources from irrigation systems developed under the Integrated Development Region strategy. To this end, it seeks to integrate the use of renewable energy supported by a clustering model, grouping different municipalities to ensure the implementation of irrigation infrastructure with democratic participation. The research locus is the state of Ceará, the only state 100% located in this Caatinga region. The solar energy potential of the Northeast region represents a major economic investment in the short term, but with a reduction in the medium and long term. Furthermore, its technical feasibility requires local energy infrastructure and, from a socio-environmental perspective, can foster cooperative and associative work through the sharing economy due to the subdivision of solar panels. Based on this scenario, the results suggest that the use of optimal location points can contribute to the development of more resilient and sustainable energy solutions, benefiting both the environmental preservation of the Caatinga region and the generation of clean energy, the latter supported by the region's solar energy potential.
Keywords: Caatinga. Distributed Energy Generation. Clustering.

The Caatinga is one of the biomes found in Brazil. Although the characteristics of a semiarid climate, with high temperatures, low humidity, and long periods of drought, are not exclusive to the country, the Northeast region has the highest concentration of Caatinga [1]. Considering drought as a target of public policies to advance Brazil's development is an important element to be observed [2]. With this in mind, Public Irrigation Projects, originated under the strategy of the Integrated Development Region, were adopted by the Brazilian government with a focus mainly on the semi-arid region, aiming at the implementation of an irrigation infrastructure with democratic participation around a group of small, medium and large producers; through the sharing of resources of irrigation systems [3].

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According to the Brazilian Government, represented by the Ministry of Integration and Regional Development, one of the main obstacles to the development of this shared culture was the availability of electricity on the properties for irrigation systems [3].

This lack of energy availability contrasts with the region's energy potential. According to the Brazilian Solar Energy Atlas [4], direct solar radiation levels occur largely in Northeast Brazil.

According to the Atlas, in addition to photovoltaic technology, electricity generation through thermal use of solar energy may be the main requirement to make the use of this generation technology viable in the region [4].

Investment in solar energy provides a greater economic return in the short term and a reduction in the medium and long term. Its technical viability requires local energy infrastructure and, from a socio-environmental point of view, it can foster cooperative and associative work through the sharing economy due to the division of solar panels [5].

When we look at the Northeast, we have that, according to the Caatinga Association, the caatinga covers the states of Piauí, Ceará, Rio Grande do Norte, Paraíba, Pernambuco, Alagoas, Sergipe, Bahia and the northern strip of Minas Gerais [1] and, among these, Ceará corresponds to the only state 100% inserted in this region of the caatinga.

A study developed with clustering models to mitigate the impacts caused by climate change, used the concept of distributed microgeneration to enable collaborative production using optimal location points, called centroids [6].

The study mapped the division of municipalities into clusters for the state of Bahia, aiming to form alliances to combine efforts focused on expansion. This study used the k-means algorithm to divide the state into subgroups, which can be representative of the application of a distributed microgeneration approach for the state of Ceará.

Based on the above information, this study seeks to develop a proposal for renewable energy viability and environmental conservation for the Caatinga region, focusing on the state of Ceará.

Using clustering models, the study aims to identify optimal locations to support the region's development through the availability of electricity on properties, targeting irrigation systems.

Materials and Methods

The methodological approach used in the construction of the clustering process was divided into three phases: Mapping of municipalities in the state of Ceará, Identification of an optimal number of clusters and Grouping of municipalities.

Mapping of Municipalities in the State of Ceará

According to the Instituto Brasileiro de Geografia e Estatística (IBGE) [7], the state of Ceará has a territorial area of 148,894.444 km² distributed among its 184 municipalities.

The mapping of these municipalities within the state was performed using the *geobr* library of the R programming language [8]. The *geobr* package allows access to data from the IBGE.

The points on the map are represented by the latitude and longitude coordinates of the municipalities that comprise the state of Ceará.

Identification of an Optimal Number of Clusters

The optimal number of clusters is identified by the model's representative points. For this identification, the Elbow model was used to select an optimal output, considering the Euclidean distance between the latitude and longitude coordinates defined in the identification of the municipalities representative points.

Grouping of Municipalities

To identify the municipalities that constitute their respective groups, the K-means algorithm was used. The K-means algorithm is the most widely used algorithm and serves as the basis for other clustering techniques used [9]. Still about the author, the algorithm uses simple principles, is easily adaptable and has good performance in real-world scenarios [9].

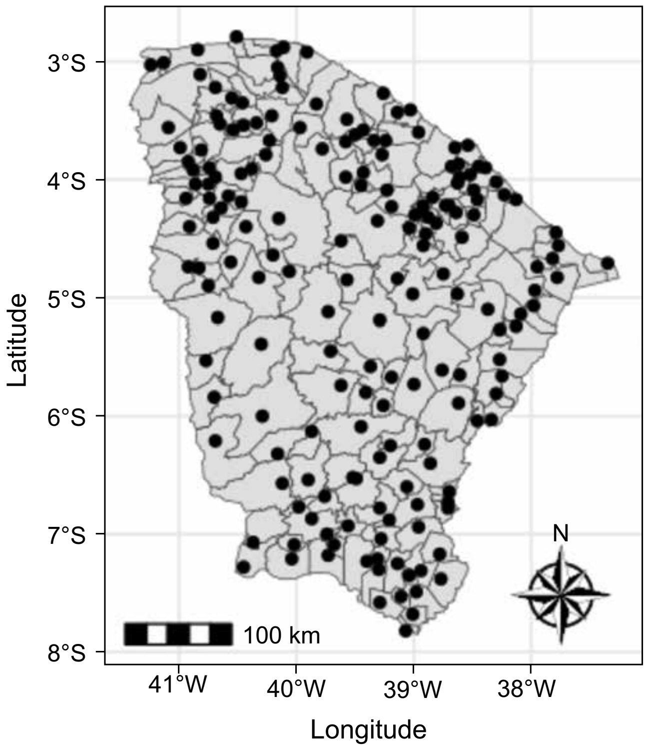
Among the identified deficiencies, already mentioned in item 2.2, also highlighted by the author, was the randomness of the process which, as a consequence, makes it impossible to guarantee an optimal number of clusters and which was overcome with the integration of the Elbow model.

Results

Based on the identified points, here called municipalities, we have their location represented based on latitude and longitude coordinates. (Figure 1) defines the reference for calculating Euclidean distances between municipalities and their respective centroids.

From the methodological approach presented, we have that the optimal number of clusters (k) represented by the Elbow method (Figure 2) identified the value of k equal to 10 for the set of municipalities used.

Figure 1. Map of the state of Ceará showing representative the points for calculating the Euclidean distance to the centroids.



This value suggests that the total number of clusters should not exceed 10, since, as shown in the graph, there is no significant change that would support expanding this scope to reduce the Euclidean distance between municipalities and their respective centroids.

Based on the k value obtained, we have the distribution of municipalities in the state represented by 10 clusters, with their respective centroids, as shown in Table 1.

The final representation of these elements indicates where each centroid should be located to ensure the shortest distance between all municipalities in the clusters.

The distribution of these centroids among the municipalities of the state of Ceará (Figure 3) within their clusters suggests the implementation of micro or mini distributed power plants, with their energy source captured through the region's renewable energy potential, aiming to collaboratively power the municipalities and provide irrigation infrastructure for environmental conservation in the Caatinga.

Discussion

The sharing economy facilitates more economically viable investments. The potential integration

Figure 2. Optimal cluster number identified using the Elbow method. Development by the authors.

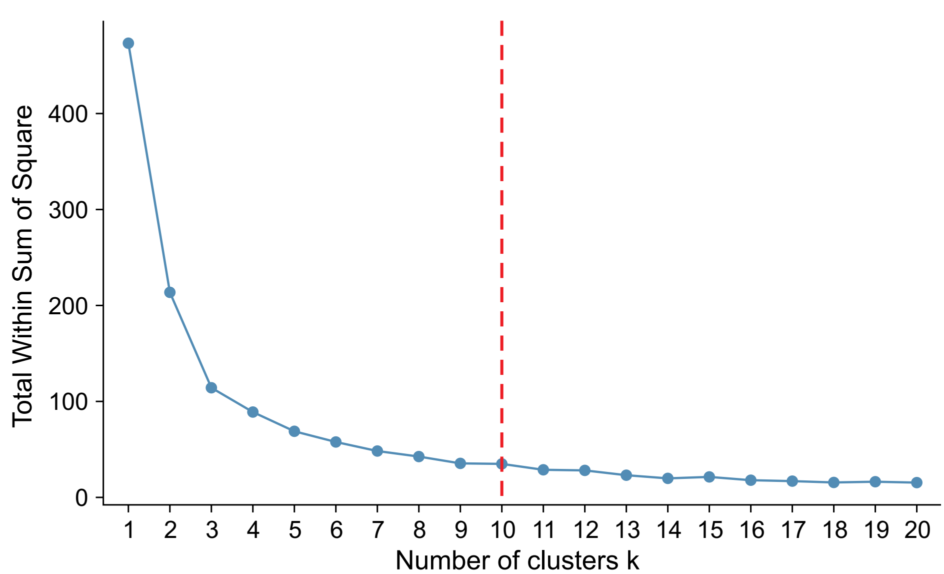
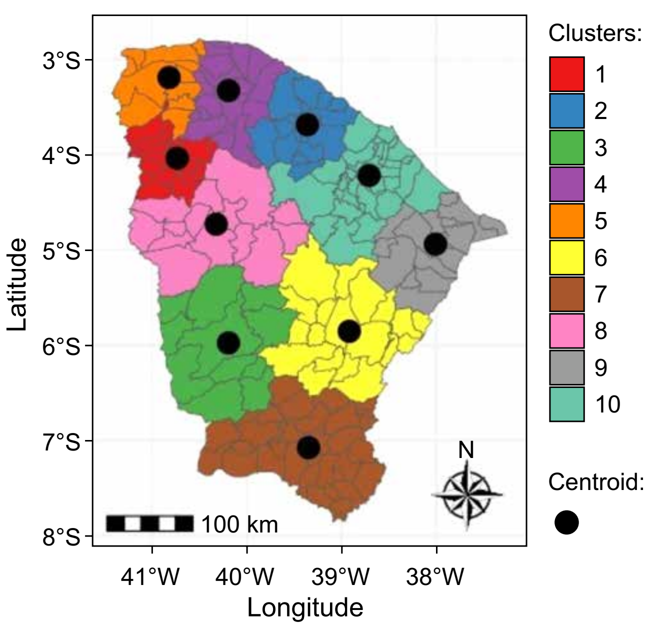


Table 1. Comparative data on the total number of municipalities in the states and their respective groups.

Centroid	Latitude	Longitude	Total Municipalities
1	-40.73412	-4.040000	17
2	-39.36187	-3.688125	16
3	-40.19364	-5.974545	11
4	-40.19333	-3.328667	15
5	-40.82000	-3.192000	10
6	-38.92053	-5.852632	19
7	-39.34971	-7.076000	35
8	-40.32286	-4.733571	14
9	-38.01214	-4.943571	14
10	-38.71152	-4.220909	33

Figure 3. Identification of Centroids on the clusters identified by the K-means Algorithm.



between the caatinga vegetation and renewable energy generation technologies, such as solar energy, constitutes a solution capable of developing sustainable energy production for the Brazilian semiarid region, ensuring the implementation of irrigation infrastructure with democratic participation.

The integration of different data sources, as well as the analysis of multiple variables, such as road infrastructure, socioeconomic factors, legal dependency, environmental characteristics, energy networks and technology, among others, are also necessary to ensure that renewable energy projects are efficient, sustainable, and adapted to local realities.

The participation of microgrid-based infrastructures, characteristic of micro and mini distributed energy generation scenarios, although conceptually treated differently, constitutes an important enabling agent for scenarios with limited energy production, especially when collaborative energy production is necessary.

Cluster quantitative identification based on methods such as Elbow can be replaced by other methods, bringing the different specificities of each municipality into closer view.

Although the various scenarios highlighted translate into reality, the existence of optimal location points based on clustering systems opens up possibilities for optimization and efficient management of energy resources. It is also noteworthy that clustering-based models aim for a decentralization process, providing greater autonomy over the grouped municipalities. They can be applied to different locations, not limited to a specific research locus, making the clustering algorithm a potential ally in constructing scenarios based on this set of characteristics.

Conclusion

The objective of this work was to propose a computacional model for low-carbon shared economy irrigation infrastructure projects focused on the development of the Caatinga region.

The use of machine learning-based methods constitutes a potential ally in research involving shared collaboration, especially in areas related to microgrid-based energy production.

These models emerge especially in decentralized settings far from large urban centers, where closer public policy engagement is necessary to promote positive changes in the current scenario, aiming to ensure a more sustainable future for present and future generations.

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Multiagent System for Discrete Manufacturing with Integration into the MES/SCADA System and Production Decision Support

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Discrete manufacturing faces significant challenges related to high variability, mass customization, and the demand for rapid responses to operational failures, which increase costs and compromise process efficiency. Industry 4.0 emerges as a response to this scenario by promoting digitalization and intelligent system integration, enabling real-time monitoring and dynamic adaptation of production. The integration between the Manufacturing Execution System (MES) and Multi-Agent Systems (MAS) becomes essential to optimize processes, enable greater decision-making autonomy, and increase the resilience of the production system. This work proposes a multi-agent approach to optimize production in discrete manufacturing environments, integrating with MES/SCADA systems and establishing the foundations for a Digital Twin with Artificial Intelligence (AI) capabilities. The methodology was applied at the Advanced Manufacturing Plant (PMA) of SENAI CIMATEC, a demonstrative Industry 4.0 environment. The initial steps involve defining the agents, modeling the system, and integrating with MES, using a Service-Oriented Architecture (SOA) to expose functionalities as microservices. The results include the mapping and classification of PMA components, as well as the proposal of a preliminary agent structure, modeled in UML and divided into two groups: Device Agents, responsible for field data collection, and Management and Analysis Agents. It is expected that the Analyzer Agent will play a key role in detecting deviations or potential failures in the process by employing AI to predict faults and suggest rescheduling. The proposed solution offers a conceptual basis that integrates traditional technologies and intelligent agents to build an AI-enabled Digital Twin, capable of supporting dynamic rescheduling and adaptive control, enhancing responsiveness to changes and unforeseen events.
Keywords: Multiagent System. Discrete Manufacturing. MES. Industry 4.0.
Abbreviations: MES, Manufacturing Execution System. SCADA, Supervisory Control and Data Acquisition. MAS, Multi-Agent System. DT, Digital Twin. PMA, Advanced Manufacturing Plant. IIoT, Industrial Internet of Things. CNC, Computer Numerical Control. MTBF, Mean Time Between Failures. OEE, Overall Equipment Effectiveness. UML, Unified Modeling Language. HMIs Human-Machine Interfaces. M2M, Machine-to-Machine.

Discrete manufacturing faces growing challenges, such as high variability, mass customization, and demand for personalized products in small batches. These factors increase the complexity of production processes, requiring efficient coordination of real-time information. The absence of systems capable of anticipating failures and responding quickly to operational disruptions results in unplanned downtime and high costs [1].

Industry 4.0 emerges as a response to the limitations of traditional models, promoting the digitization of manufacturing and intelligent integration between machines, processes, and systems [2]. In this context, technologies continuously connect the physical and digital worlds, enabling real-time monitoring, predictive analytics, and operational simulations. This digital layer, coupled with productive assets, allows for dynamic adjustments and more agile decisions, making processes more responsive and efficient [3].

The integration of the Manufacturing Execution System (MES) with this digital infrastructure and Multiagent Systems (MAS) is fundamental to smart manufacturing. MES, traditionally responsible for mediating planning and operations, expands its role by incorporating updated production data, now also acting in the control and optimization of processes [4]. This synergy allows for quick reactions to events in real time, adjusting flows and priorities autonomously and contextually.

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With the addition of MAS, the architecture gains autonomy and adaptability. Distributed agents collaborate in resource allocation, fault management, and production reconfiguration in the face of variations or disturbances. This decentralized approach favors local decisions aligned with global objectives, promoting a more resilient, flexible production environment capable of responding quickly to the demands of mass customization and the uncertainties of industrial operation [5].

This paper aims to answer the following question: How can an MAS be designed to optimize discrete manufacturing, considering integration with MES/SCADA systems?

It is proposed to develop a MAS for discrete manufacturing, integrated with MES/SCADA systems, aiming to establish the foundation for the development of a Digital Twin (DT) with Artificial Intelligence (AI) capabilities, able to support autonomous decision-making for rescheduling and adaptive production control.

Related Works (Art Study)

In the study conducted by Nie and colleagues [1], a decentralized resilient scheduling method for flexible workshops is presented, structured in three hierarchical levels: shop floor, service unit, and machine. Each agent responds locally to disturbances using buffers, excess capacity, or lead time, and adopts a collaborative adaptive decision-making mechanism to enhance the system's resilience and efficiency.

Siatras and colleagues [4] demonstrates the use of a MAS for decentralized production scheduling in the bicycle industry. Agents manage task allocation in segments such as painting and assembly, in conjunction with DT and Asset Administration Shells, enabling flexible, parallel, and coordinated decisions to avoid bottlenecks and optimize performance.

Garcia, Oregui, and Ojer [6] proposes a framework with a MAS distributed between cloud and edge for collaborative production control. The use of DT and Industrial Internet of Things (IIoT) enables real-time data collection, optimizing resource allocation and supporting self-adaptive decisions in complex and dynamic production environments.

The systematic review presented by Kalyani and Collier [7] highlights the importance of MAS in the implementation of DT. Agents provide autonomy, scalability, and intelligence to DT, supporting decision-making, simulation, and operational efficiency, especially in manufacturing contexts.

In the work of Lyozin and Berger [8], a MAS is applied with DT for modeling production processes, aiming to reduce inefficiencies, downtime, and resource waste. The proposed approach allows dynamic rescheduling of only the affected part of the production and adopts an integrated classification function to maximize efficiency.

Kim and colleagues [9] proposed the integration of a MAS with reinforcement learning to create an intelligent manufacturing system. Machines with autonomous agents learn and make adaptive decisions through distributed negotiation, focusing on task prioritization and continuous performance improvement.

In Nie and colleagues [10], the MAS is applied for optimized manufacturing control, focusing on reconfiguration and agile response of the smart shop floor via DT. Agents represent people, equipment, and materials, enabling communication and autonomous decisions.

The analyzed studies present relevant advances in MAS for intelligent manufacturing. They cover resilient scheduling, collaborative control with DT and IIoT, decentralized scheduling, and the use of reinforcement learning. Despite this, the studies still show limited exploration of direct integration with management systems. This article proposes a MAS that architecturally integrates MES/SCADA systems. The proposal presents a conceptual foundation that promotes cooperation between traditional systems and autonomous agents and aims to build a digital twin with AI to support rescheduling and adaptive production control.

Materials and Methods

For the development of the proposed MAS, the Advanced Manufacturing Plant (PMA), located at SENAI CIMATEC in Salvador/BA, was selected. It is a pilot Industry 4.0 manufacturing plant with a didactic and demonstrative purpose. This environment is a scaled-down representation of industrial operations, with one of its objectives being to serve as a laboratory and testing space for the validation of methods, architectures, and emerging technologies in the context of Industry 4.0.

The PMA allows investigation and validation of intelligent management methods applied to customized production in flexible assembly lines, as well as illustrating the organizational capacity of cyber-physical systems in complex industrial environments. Focusing on the manufacturing and operation of processes related to finishing components such as covers and bases of pneumatic cylinders, the PMA integrates CNC machines and other automated stations to compose realistic industrial scenarios.

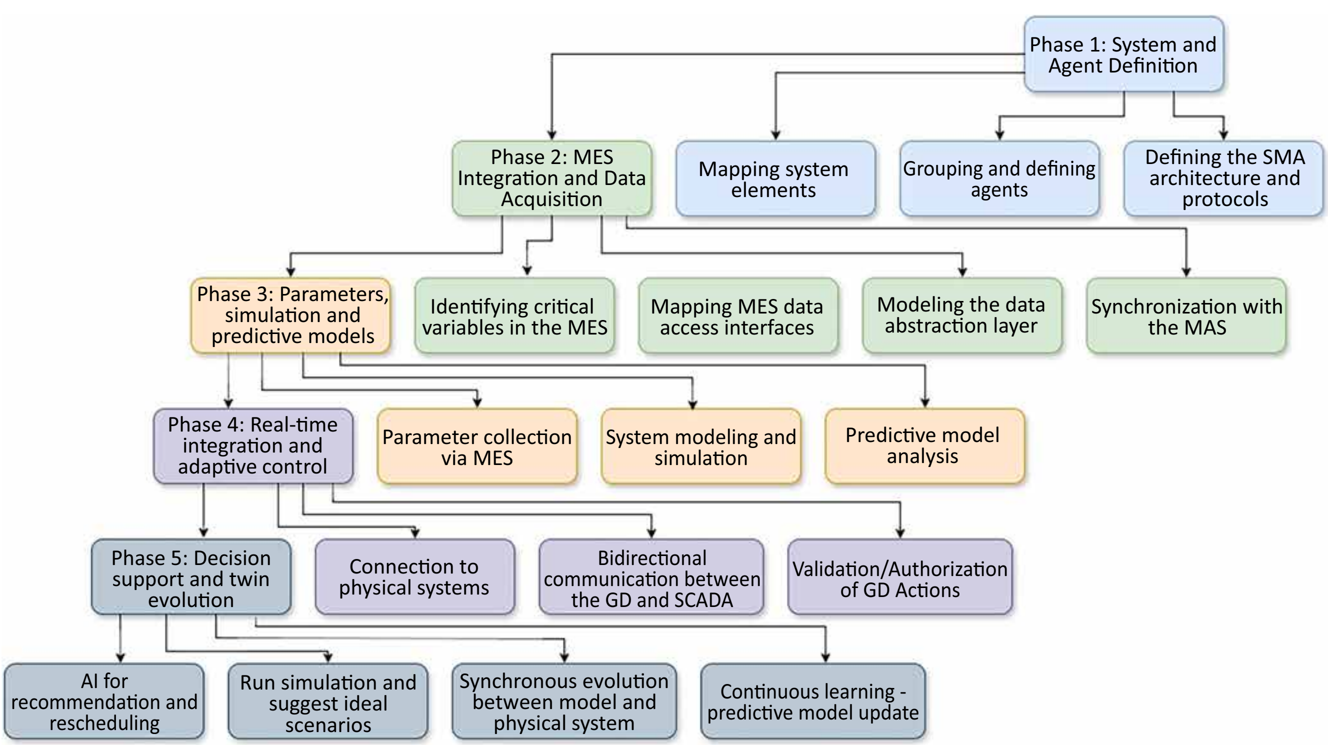
Based on a detailed analysis of the PMA production processes, a methodological framework was developed, illustrated in the flowchart in Figure 1. Phase 1 is dedicated to defining the system and agents, and Phase 2 focuses on integration with the MES for acquiring essential data.

The subsequent stages, from Phase 3 to 5, encompass modeling and predictive simulation, real-time integration, and adaptive control, resulting in decision support and continuous evolution of the digital twin. These stages will be addressed in future work.

System and Agentes Definition

In the first phase, the process for which the MAS will be developed is defined. In this work, the system is developed to manage a flexible assembly line aimed at producing customized items, based on the SAMOM model proposed by Cruz and Lepikson [11].

Figure 1. Methodological flowchart of the system for manufacturing with MES/SCADA integration.



Source: Author's own.

This stage requires detailed identification of physical and logical components, which will be abstracted as autonomous computational entities. Machines, workstations, products, operators, sensors, and production orders are mapped according to their function and level of abstraction: machines and workstations are grouped as productive resources, products and orders as flow entities, and operators and sensors as human and perception interfaces.

Each element is translated into an agent with well-defined roles in the system. These agents are specified according to their roles and responsibilities in the production cycle, their perception and action capabilities, and the types of information they must share.

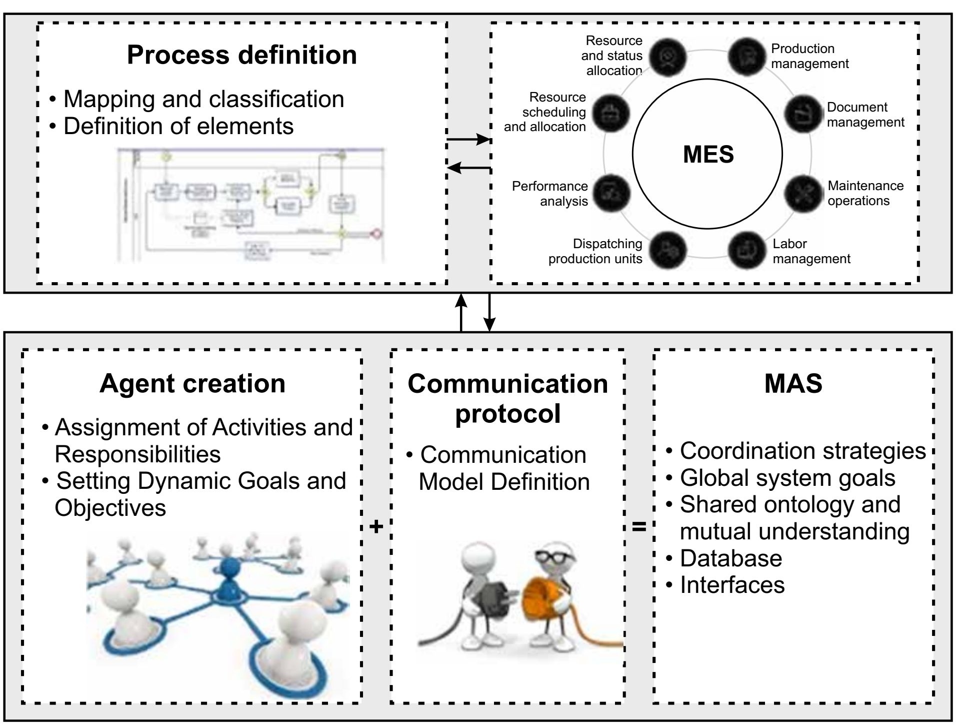
Agents are defined as computational elements capable of performing three main functions: perception (receiving signals and data), processing (executing calculations, logic, and inferences), and action (sending new signals and data). Another important principle is autonomy and negotiation among agents. Each agent can act and decide independently, interacting with other agents through negotiations to achieve its objectives.

MES Integration and Data Acquisition

The proposed integration between MES, SCADA, and MAS aims to establish a collaborative and adaptive architecture guided by Industry 4.0 principles, as described in Figure 2. The model starts from the understanding that for effective operation of autonomous agents, structured and real-time access to data generated by MES is essential, organized into critical categories reflecting the state of production, resources, and quality. To enable agents to make informed decisions, it is crucial to identify which MES data points are critical.

Among the main data points that must be monitored are: production scheduling and dispatch of production units; work-in-progress control and product tracking; status and allocation of machines, operators, and resources; material availability and inventory control; quality data of processes and products; and continuous performance monitoring

Figure 2. Representation of the integration between MES and MAS.



Source: Adapted from Tanajura, Lepikson and Freires [12].

based on key performance indicators (KPIs), such as cycle time, rework rate, takt time, Mean Time Between Failures (MTBF), and Overall Equipment Effectiveness (OEE) [13].

The modeling and access to this data are structured through a Service-Oriented Architecture (SOA) approach, in which MES functionalities (including services routed via SCADA) are provided as microservices consumable by agents. SCADA collects field signals by exposing services that both feed the MES and can be accessed directly by agents for low-latency operations.

The MES consolidates histories, processes KPIs (availability, takt time, output rate, cost, and quality), and provides its own microservices to the agent layer, which, decoupled from physical specifics by an abstraction layer in UML, can operate as reactive (simple data collection) or cognitive (AI/ML).

Expected Results

The components of the PMA were mapped and classified so that the agent structure to be implemented includes several functional classes that interact with each other to make production smarter and more adaptive. These agents were organized into two main groups: Device Agents, which represent the physical elements of the shop floor, and Management and Analysis Agents, which operate at higher levels of decision-making.

The modeling of agents was conducted using UML diagrams to represent their functions, interactions, and hierarchical relationships. A preliminary structural view of the agents is proposed, identifying only the main classes without detailing specific methods and attributes. Figure 3 illustrates this proposed organization of agents in the MAS, highlighting the planned types and their general relationships within the architecture.

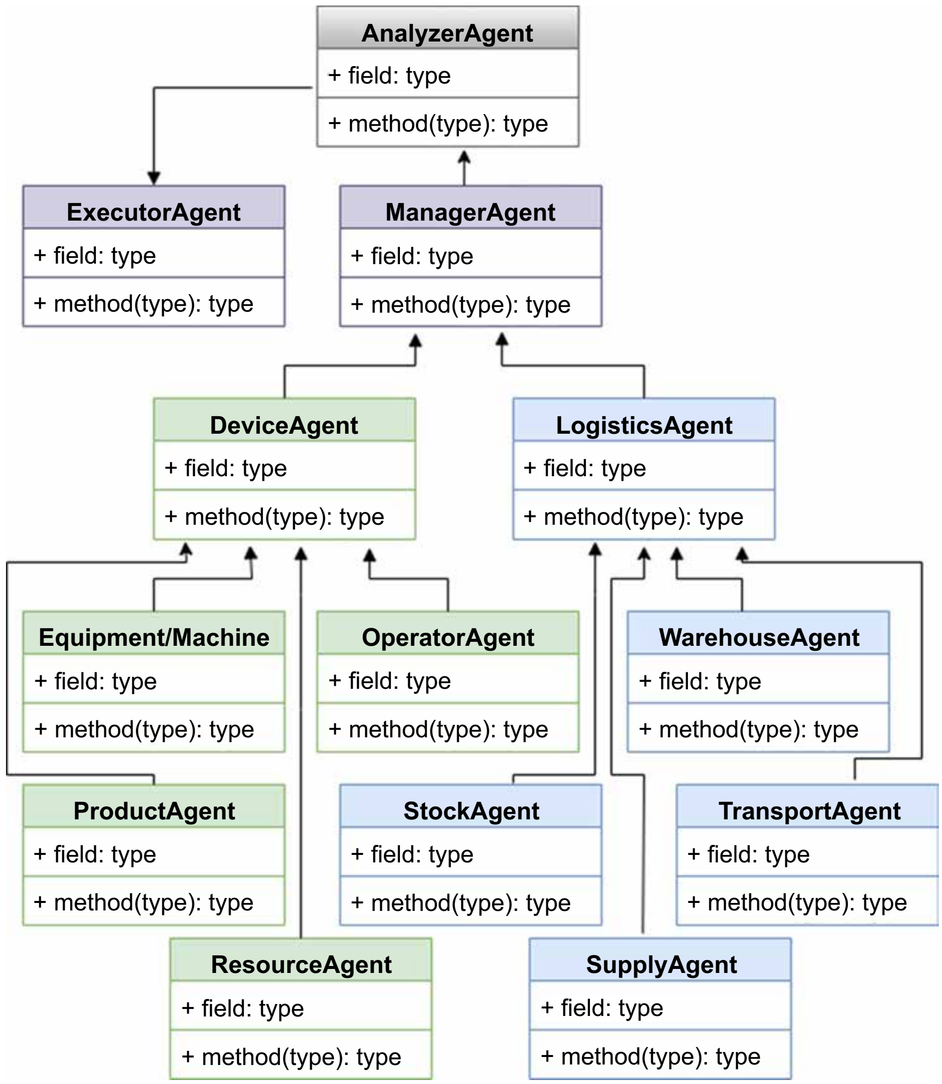
Device Agents are responsible for digitally representing the physical components of the factory and form the basis for the DT. Among them, the Equipment/Machine Agent stands out, which collects data from sensors, reports the machine's status (such as available, operating, or in fault), and also receives commands to change its operation. The Operator Agent represents human operators and is responsible for interacting with HMIs (Human-Machine Interfaces), providing information about their activities and availability. The Product Agent follows the product during its manufacturing, recording its current state, location, and the processes it has undergone. Finally, the Resource Agent is responsible for digitally representing the inputs and utilities used during the production process, such as compressed air, electrical power, and raw materials.

Management and Analysis Agents operate at a higher level, bringing intelligence to the system. The Analyzer Agent, for example, functions as the 'brain' of the operation. It receives data from Device Agents, the Logistics Agent, and the MES, and analyzes production scenarios. This agent is expected to use AI techniques to predict failures and propose rescheduling solutions. The Executor Agent comes into action after decision-making, being responsible for transforming the Analyzer Agent's recommendations into concrete commands sent to the Device Agents. It also monitors the execution of actions to ensure everything proceeds as planned. The Manager Agent can make decisions based on information from other agents. Its scope may involve a specific workstation or even a complete line, acting as a mediator between the Analyzer Agent and the other agents.

Communication among all these agents follows a service-oriented architecture (SOA) logic, enabling flexibility and integration. Within this flow, MES and SCADA play fundamental roles. Device Agents are the first to collect data directly from the shop floor, such as status, availability, and performance information, passing these data to the Manager Agent. MES provides important operational data, such as production orders, performance indicators, and process history. SCADA, in turn, complements this communication by providing real-time monitoring and control data.

Based on this data, the Analyzer Agent is expected to play a vital role in detecting deviations or potential failures in the process. From this perspective, AI

Figure 3. UML diagram of the organization of agents in the MAS.



models are intended to be employed to predict system behavior and simulate different production rescheduling alternatives, aiming to mitigate impacts. During the simulation, 'negotiations' may occur between agents, such as the Analyzer Agent consulting the Device Agent about its availability or the Logistics Agent about material supply. Based on these interactions, the Analyzer Agent selects and proposes the best possible scenario, considering criteria such as lowest cost or minimal downtime.

After the best alternative is defined, the Analyzer Agent sends this rescheduling proposal to SCADA. This proposal is then presented to the human operator, who must validate it. Approval by the operator acts as a trigger to activate the Executor Agent. After this validation, the Executor Agent sends the new commands to the Device Agents, which in turn pass these instructions to the physical equipment.

Interaction among agents occurs through cooperation, negotiation, competition, and coordination. For interoperability, the model uses M2M for direct communication, OPC UA for industrial integration, and Web Services (REST APIs with HTTP and JSON) for data exchange with MES. Technologies such as WebSocket, XML, and FIPA-ACL will also be considered. Alternative protocols (MTConnect, MQTT) and legacy ones (Modbus, OPC Classic) may be used occasionally.

Each agent recognizes the context and priority, coordinating with the MES or acting autonomously to avoid redundancy. This architecture aims for efficient, safe, and adaptive manufacturing operations, compatible with Industry 4.0, DT, and intelligent automation.

The synchronization of SCADA, MES, and MAS thus ensures fidelity and agility in communication between the physical world and its digital representation. Figure 4 demonstrates this integration with the PMA.

Conclusion

This work presents a MAS approach to optimize discrete manufacturing through a collaborative and adaptive architecture. The proposal structurally integrates MES/SCADA systems, bringing production control closer to the distributed intelligence provided by autonomous agents. The literature review revealed that direct integration between management systems and MAS is still underexplored.

The proposed solution establishes a conceptual foundation that combines traditional technologies and intelligent agents, with the goal of building a Digital Twin equipped with AI capabilities to support dynamic rescheduling and adaptive production control, enhancing responsiveness to changes and unforeseen events.

For future work, the modeling of the MAS is expected to continue, with an emphasis on Phases 3 to 5, focusing efforts on the development of the DT.

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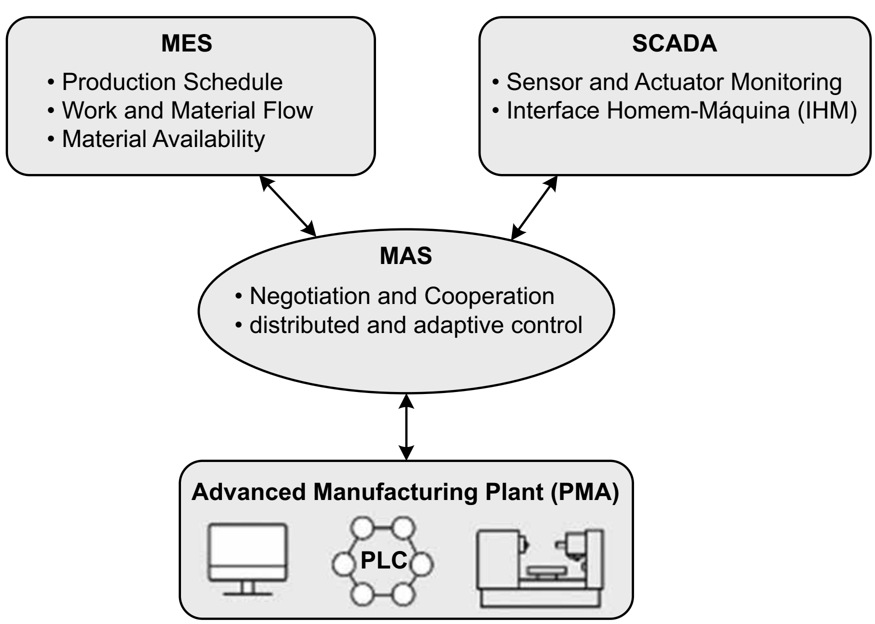
Figure 4. Integration between MES, SCADA, MAS, and the Advanced Manufacturing Plant (PMA).



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Optimization of Code for Scalability of Deep Reinforcement Learning Agents in Slow and Stochastic Industrial Process Patterns

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This work investigates the impact of code optimization techniques on the scalability and training time of deep reinforcement learning (DRL) agents applied to stochastic and slow-dynamic industrial process control environments. DRL combines deep learning and reinforcement learning to address high-dimensional decision-making problems, but it often demands significant computational resources and time, especially in complex industrial scenarios. To address these challenges, this research explores the use of vectorization, parallelism, and hyperparameter optimization via Optuna to improve performance and training efficiency. Experiments were conducted using the "TempControl-v0" environment from the PIDGym library, simulating thermal inertia processes akin to industrial furnaces. Key metrics analyzed include total training time, average episode reward, and CPU/GPU utilization. The results demonstrate that strategic code optimization can significantly enhance the performance and scalability of DRL agents, making their application more feasible in real-world industrial contexts.
Keywords: Code Optimization. Deep Reinforcement Learning. Hyperparameter Tuning. Industrial Process Control. Parallel Computing.

Artificial Intelligence is a branch of computer science that seeks to build mechanisms, physical or digital, that simulate the human ability to think and make decisions [1]. These mechanisms generally depend on training and testing to build their knowledge and application in different areas.

In this context, within the field of Artificial Intelligence, a specific training approach known as Deep Reinforcement Learning (DRL) stands out. According to Arulkumaranand colleagues (2017) [2], this technique has made it possible to solve problems that were previously intractable due to the large number of possible states and actions.

However, Reinforcement Learning (RL) combined with Deep Learning (DL) can become costly as the problem size increases. First, as argued by Bianchi and Costa (2004) [3], unfortunately, the convergence of RL algorithms can only be achieved after extensive exploration of the state-action space, which is generally time-consuming. Moreover, DL algorithms are highlighted by Araújo (2024) [4] as "one of the most resource- and energy-intensive tasks," further warning that training without hardware accelerators can take several days.

With this, performance bottlenecks can be critical when combining both methods to generate deep reinforcement learning. Especially when applied to slow and stochastic industrial process routines. According to Silva (2024) [5], a stochastic process is characterized by uncertainty and the description of the future in terms of probabilities that model the presence of randomness in the system. Subsequently, Cendron (2022) [6] corroborates the idea that manufacturing industries face dynamic and stochastic production environments. That is, with random industrial environments, deep reinforcement learning may face long training periods due to the high rate of variables or states in process routines to be learned, promoting a slow learning dynamic to achieve a small error.

Parallel to the previous context, code optimization stands out. Passos and colleagues (2022) [7] highlight in their study that in various applications, the need emerges to build a solution that is fast or

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that makes maximum use of available hardware, thus demanding performance optimization techniques. From this, the idea of optimizing code and/or system algorithms stands out, such as those of deep reinforcement learning in industrial processes, to improve performance, speed, and accuracy.

Therefore, the general objective of this research is to analyze the impact of code optimization on the scalability and training time of deep reinforcement learning agents applied to the control of slow and stochastic industrial processes. Additionally, the following specific objectives are highlighted for the development of this research: (i) to investigate vectorization, parallelism, and parameter tuning applicable to deep reinforcement learning algorithms, (ii) to evaluate the impact of these strategies on training time and agent performance through experiments, and (iii) to analyze the scalability of the optimized algorithms in different simulated industrial scenarios with varying levels of complexity.

Theoretical Foundation

Code Optimization Techniques

Among the aforementioned code optimization strategies, parallelism stands out as a primary approach. According to Wilkinson and Allen (2005) [8], parallel programming, within the computational context, aims at executing multiple tasks or different parts of the same task, concurrently, leveraging multiple processing cores to enhance program execution and solve complex problems more efficiently in terms of time.

When considering the context of Deep Reinforcement Learning (DRL), there is clear evidence of success in solving problems that were once considered intractable. However, solving such problems imposes a high computational cost due to the large number of possible variables. According to Arulkumaran and colleagues (2017) [2], “Deep learning enables RL to scale to decision-making problems that were previously intractable, i.e., settings with high-dimensional state and action spaces.” The training of these deep learning models not only demands computational and energy resources, but can also take a long time without proper hardware support, as previously mentioned by Araújo and colleagues (2024) [4]. This highlights the importance of using GPUs and TPUs as strategies for optimizing time and resource consumption, as they are designed for performing massive operations simultaneously.

Considering the issues mentioned above, it is evident that the performance bottleneck can become even more critical when implementing DRL in the context of industrial processes characterized as stochastic and slow in dynamics. These processes involve uncertainty and high variability, requiring extensive exploration of the state and action space, which results in long training times. Therefore, code optimization through parallelism becomes essential for the scalability and feasibility of these agents in complex industrial environments.

From this perspective, vectorization can be addressed. Allen and Kennedy (1984) [9] approach vectorization as a transformation of serial code reordering, adapting it to be executed more efficiently on architectures that support vector operations, allowing a single processor instruction to operate on multiple data simultaneously, thus enabling the processor to process a set of elements in a single step, offering significant performance gains. Araújo and colleagues (2024) [4] address the idea that DRL models, especially those with deep neural networks, execute a massive volume of numerical operations, making the importance of vectorization in optimizing this process notable, particularly based on observations made by Nuzman and Henderson (2006) [10], who understand the effectiveness of vectorization when applied to repetitive operations, such as mathematical calculations on arrays and matrices.

Finally, parameter adjustments are evidenced through Optuna, which Akiba and colleagues (2019) [11] break down its dynamic structure (define-by-run): "Optuna formulates the hyperparameter optimization as a process of minimizing/ maximizing an objective function that takes a set of hyperparameters as an input and returns its (validation) score". This approach is essential for dealing with complex and dynamic environments, allowing the construction of search spaces that evolve according to the experiment. Another point to be highlighted is its efficient optimization with "pruning", which enables scalability, since it drastically reduces the time spent on unpromising episodes, as it prematurely interrupts experiments that present unsatisfactory performance, saving computational resources and accelerating agent convergence.

Deep Reinforcement Learning (DRL)

It is considered that deep reinforcement learning is the union of reinforcement learning techniques with deep learning. In this sense, Kaelbling, Littman and Moore (1996) [12] state that reinforcement learning (RL) is "the problem faced by an agent that must learn behavior through trial-and-error interactions with a dynamic environment," that is, a behavior learning training based on trial-and-error iterations in a dynamic environment. In the study on the use of RL in mobile robots, Faria and Romero (2002) [13] highlight that this learning is based on the idea that if an action is followed by satisfactory states, or by an improvement in the state, then the tendency to produce this action is increased, that is, reinforced.

The action of a satisfactory state is increased or decreased from the numerous trial-and-error iterations within the state space and, sometimes, propagated through time. However, one of the necessary conditions in which RL algorithms can find an action policy is the complete exploration of the state space, normally impossible in practical situations [13]. Practical situations such as in random industrial processes or those with slow dynamics can become challenges for RL, considering that the random state space is large and dynamic with high risk in industries with large-scale routines.

Regarding the second object of the DRL union, deep learning is described by Bochie and colleagues (2020) [14] as an area of machine learning characterized by the extraction of complex representations from simpler representations. Pereira (2017) [15] corroborates the concept by stating that this area can be considered as an intersection between the areas of neural networks, graphical modeling, optimization, pattern recognition, and signal processing.

As stated by LeCun, Bengio, and Hinton (2015) [16], deep learning "is making major advances in solving problems that have resisted the best attempts of the artificial intelligence community for many years." The authors explain that, ten years ago, this learning model began solving problems that had long resisted all attempts by the artificial intelligence community, highlighting the vast potential for applications in current problems that are still in the discovery phase.

However, regarding the challenges of deep learning, Bochie and colleagues (2020) [14] state that typically, deep learning requires models that capture the non-linearities of the problem, making the modeling relatively more complex. This means that despite the advantages of deep learning, its application demands more complex models and longer training processes, resulting in higher computational requirements and additional difficulties in development.

Deep reinforcement learning is presented in the study by Arulkumaran and colleagues (2017) [2] as "represents a step toward building autonomous systems with a higher-level understanding of the visual world". This statement emphasizes that DRL goes beyond simple visual data processing, developing a broader understanding of the environment that allows autonomous systems to make more effective decisions in complex situations.

Finally, Arulkumaran and colleagues (2017) [2] highlight that "DRL can deal efficiently with the curse of dimensionality, unlike tabular and traditional nonparametric methods". The "curse of dimensionality" represents one of the main obstacles in traditional reinforcement learning problems, where the number of possible states grows exponentially with the dimensionality of the problem. DRL overcomes this limitation through the ability of deep neural networks to approximate complex functions in high-dimensional spaces, enabling applications in real-world problems that would be intractable with conventional methods.

Materials and Methods

Environment Structure

To investigate the impact of code optimization on the scalability of training deep reinforcement learning agents, a custom environment named "TempControlEnv" was developed using the "Gymnasium" library. The environment models the evolution of temperature over time based on the action applied by the agent, with variations that include efficient heating, thermal loss, random noise, and external disturbances. Aiming to incorporate high-precision computational bottlenecks, the environment assigns a quadratic term (temp_diff**2) to heat loss and a temperature update using the 4th-order Runge-Kutta method, which increases the complexity and computational cost of execution. Additionally, at each simulation step, matrix multiplication and singular value decomposition are performed to create a heavy and constant CPU workload.

The action space has one dimension and is continuous, represented by a value between -1 and 1, thus corresponding to the intensity of cooling or heating. It can vary according to the enabled configurations, having in its basic form two main variables: the temperature error relative to the setpoint and the derivative of the error, allowing the modulation of the environment's complexity, making it suitable for comparative performance testing of algorithms.

The environment features a reward function composed of a penalty proportional to the absolute error, an additional penalty for large variations between sequential actions, extra reward when the error is below a precision threshold, and an additional penalty for oscillation, based on the standard deviation of the error history.

Comparison Metrics

The metrics used for analysis within this environment are the training time to demonstrate the effectiveness of optimizations and the average reward per episode, mentioned by Kayal and colleagues (2025) [17] as fundamental for measuring the agent's convergence and effectiveness by summing the total rewards received by the agent throughout an episode, along with the reward standard deviation to measure control stability and penalize oscillations.

Araújo and colleagues (2024) [4] address another analysis point that involves the variation in computational performance based on GPU/CPU usage, since the chosen optimization techniques aim to result in better CPU core utilization and better hardware bandwidth usage, which should directly impact CPU usage rate and reduce the average load on the GPU/CPU.

To develop the evaluation of the impact based on training time and performance, timing functions were used to record the total training time. Regarding the reward per episode, as mentioned by Kayal and colleagues (2025) [17], the rewards are accumulated from each episode for all parallel actors and then averaged across the actors.

As for GPU/CPU usage metrics, performance analysis is conducted using the Python libraries "psutil" and "pynvml," with "psutil" responsible for monitoring the average CPU usage throughout agent training and execution, and "pynvml" enabling access to GPU utilization metrics. These tools allow for a correlation between the applied optimizations and the computational resources used, enabling a detailed analysis of the performance of the applied techniques.

Models for Testing

For this study, four models were selected: the "Base" model without any optimizations; the "Optuna" model using the tool of the same name along with simple vectorization via "DummyVecEnv"; the "Parallel" model using the aforementioned parallelism technique in combination with vectorization implemented through the "SubprocVecEnv" (Subprocess Vectorized Environment) tool; and finally, the "Parallel + Optuna" model combining both methods.

Results

Standard deviation of rewards was also calculated across configurations. The Base model had the highest deviation with 919.69, while Optuna had the lowest with 661.35. The Parallel and Parallel + Optuna models had deviations close to the base, with 898.89 and 907.11 respectively.

From the table, the impact of optimization strategies on training efficiency can be observed. It shows that the version using "Optuna" achieved a higher average reward and lower variability in standard deviation. On the other hand, "Parallelism + Optuna" was the fastest in training time, while the "Parallelism" test had the lowest CPU usage (5.34%).

Discussion

Impact of Optimizations on Training Time

Based on the results obtained, a drastic reduction in training time is evident in the approaches using parallelism, clearly demonstrating the influence of parallel environments on training time reduction, with a clear decrease compared to the baseline. This approach proves essential for scaling DRL agents in complex environments.

Impact of Optimizations on Agent Performance

Another noteworthy point is the performance gain through hyperparameter optimization (Optuna test), resulting in more effective control and outperforming the baseline as indicated by the average reward and standard deviation values.

Speed *vs*. Quality

Given the results presented, there is an evident trade-off between training time efficiency and the final performance of the agent. The hyperparameter optimization approach achieved the highest reward and lowest standard deviation, while the approaches using parallelism did not reach this performance despite being faster. This is likely due to the way experiences are collected. In sequential training, although slower, exploration is more focused since the gradient used to update the neural network is based on experiences from a more consistent policy, favoring higher-quality convergence. In parallel training, experiences are collected simultaneously from different trajectories and time steps, which speeds up data collection but may result in poorer gradients, causing the agent to converge to a good solution, but not necessarily the best possible one.

Conclusion

In conclusion, this work achieves its main objective of investigating the impact of code optimization techniques—specifically parallelism, hyperparameter tuning, and vectorization—

Table 1. Results for each method.

Configuration	Average Reward	Average Time(s)	Average CPU(%)
Base	-36298.78	310.9	36.7
Optuna	-35823.4	282.4	45.3
Parallel	-37111.97	153.7	5.3
Parallel + Optuna	-37174.18	120.1	21.7

on the scalability and performance of deep reinforcement learning agents when applied to industrial environments with slow and stochastic dynamics. Hyperparameter optimization via Optuna, combined with simple vectorization, proved to be crucial for improving the agent's final performance, resulting in a more effective and stable control policy, as evidenced by the average reward and standard deviation.

Parallelism, in turn, implemented through a complex vectorized environment, proved to be an indispensable tool for scalability, drastically reducing training time. Another key point is the identification of a trade-off between training speed and solution quality, where fast, parallelism-based approaches did not produce agents with satisfactory final rewards.

It is therefore understood that the choice of optimization strategies is contextual to the project's priorities. When rapid prototyping and agile interaction are desired, parallelism is the superior approach; however, for maximum performance extraction, hyperparameter optimization becomes more advantageous. These findings have direct implications for the practical application of DRL, where development time and final control effectiveness are critical factors.

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Energy Justice and Microgrids in Vulnerable Urban Areas: A Sustainable Approach

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This article explores the critical intersection between energy justice and the transformative role of microgrids in socially vulnerable urban areas. The research addresses inequalities in energy access that affect these communities, highlighting how the implementation of microgrids can promote equity, resilience, and sustainable development. The social, economic, and environmental benefits of integrating microgrids were analyzed, including benefits to communities, fostering the local economy, and reducing carbon emissions. The results achieved demonstrate that microgrids not only ensure a more reliable and accessible energy supply but also empower communities, allowing them greater control over their energy resources. The analysis of global success cases illustrates the viability and positive impact of these solutions, despite technical, financial, and regulatory challenges. We conclude that microgrids are an ally in building a more just and equitable energy future, with significant implications for public policies and future research aimed at overcoming energy poverty and promoting urban sustainability.
Keywords: Energy Justice. Microgrids. Social Vulnerability. Renewable Energy. Sustainable Development.

Equitable access to energy remains one of the main challenges in vulnerable urban areas, where structural inequalities persist that directly impact the quality of life and socioeconomic development [1].

These populations face not only precarious energy supply, but also high costs, deficient infrastructure, and environmental risks that amplify social and economic exclusion [2,3]. In this context, energy justice presents itself as a field of study that seeks to understand and mitigate disparities in access, promoting sustainable, safe, and socially just solutions.

Among the emerging alternatives, microgrids stand out, decentralized systems for energy generation, storage, and distribution that operate either integrated with or isolated from the main grid [4].

By allowing greater energy autonomy, integration of renewable sources, and strengthening of local infrastructure, microgrids emerge as a viable alternative to face the challenges posed by energy poverty, especially in communities with low socio-environmental resilience [5].

Such systems also enable new community arrangements and sustainable business models, aligning with a more inclusive energy transition.

Considering these premises, this study seeks to critically analyze the potential of microgrids in promoting energy justice in vulnerable urban contexts.

The investigation focuses on identifying critical dimensions of energy injustice, evaluating the effectiveness of microgrids in terms of access, reliability, and sustainability, and formulating applicable guidelines for their implementation, with a view to maximizing community benefits and overcoming technical and institutional challenges.

Energy Justice in Vulnerable Areas

Energy justice seeks to ensure that the benefits and burdens related to energy production, distribution, and consumption are shared equitably among all individuals, regardless of their location, socioeconomic status, or origin [1]. In vulnerable urban areas, poverty and precarious infrastructure frequently limit access to adequate energy services, reflecting in high costs, insecurity, and

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exclusion [2]. These challenges can manifest in the form of energy poverty, environmental risks, and vulnerability to disasters.

The understanding of social vulnerability and its relationship with energy access varies according to the context. In Chile, for example, the condition of immigrants can represent an additional barrier to accessing energy services [4]. In Spain, low-income communities are frequently the most exposed to the effects of pollution associated with energy generation and use [5]. In the United Kingdom, energy poverty remains a relevant factor that affects the health and well-being of millions of families [6]. In the United States, the lack of access to reliable energy intensifies the impacts of extreme climatic events on socially vulnerable populations [3].

In India, the absence of basic electricity infrastructure directly compromises areas such as education, health, and income generation, perpetuating cycles of exclusion [2]. In South Africa, issues such as food insecurity and inequality are strongly linked to restricted access to energy, affecting essential daily practices [7]. In Australia, demographic and economic factors contribute to the vulnerability of remote communities, which face difficulties in accessing modern energy solutions [8].

These international experiences suggest that contexts of social vulnerability are multifaceted and require specific approaches to promote energy justice. The formulation of public policies and technical strategies must consider these variables so that the adopted solutions are effective, sustainable, and adapted to local realities.

Microgrids as a Solution: Functioning and Benefits

Microgrids are configured as decentralized energy systems that integrate generation, storage, and distribution of energy, capable of operating interconnected to the main electrical grid or autonomously. This characteristic provides them with flexibility and resilience in the face of conventional supply failures [9]. By incorporating renewable sources, such as solar and wind, and storage technologies, these systems enable the diversification of the local energy matrix and contribute to reducing dependence on fossil fuels.

In urban vulnerability contexts, microgrids represent a promising alternative to mitigate the impacts of energy poverty. Their implementation can expand energy access, improve supply reliability, and enable more sustainable practices in energy consumption and resource management [5]. Decentralization also allows for greater community autonomy, favoring the adaptation of solutions to local realities and strengthening technical and organizational capacities [6,10].

From an environmental perspective, the use of renewable sources associated with microgrids can contribute to the mitigation of greenhouse gas emissions and atmospheric pollutants, aligning with global sustainability goals and climate change combat [11]. Additionally, the reduction of technical losses in distribution and the possibility of managing local demand make microgrids more efficient systems [11,12].

In socioeconomic terms, studies demonstrate that the installation of microgrids can generate job opportunities, foster local businesses, and stimulate more participatory energy governance models [6,10,13]. Distributed generation can be converted into a source of income for communities, through the commercialization of energy surpluses, or in the reduction of household electricity expenses. These initiatives contribute to strengthening the local economy and community empowerment, especially when articulated with public policies and technical training programs.

Despite the identified benefits, the adoption of microgrids still faces barriers related to the initial implementation cost, technological complexity, and the need for regulatory adjustments. These limitations demand coordinated actions among governments, the private sector, and civil society to enable their widespread diffusion.

Integration of Renewable Energies

The integration of renewable sources is one of the main components of microgrids, especially in vulnerable urban contexts [12]. Sources such as solar photovoltaic, wind, and biomass can be adapted in a decentralized way, meeting local needs. This approach contributes to the diversification of the energy matrix and to the strengthening of energy supply security.

Renewable generation associated with storage technologies, such as batteries, allows for the continuity of supply even in adverse conditions, such as conventional grid interruptions or climatic variations [11]. This aspect is particularly relevant in regions with fragile infrastructure, where the intermittency of energy compromises the functioning of schools, health posts, and small businesses.

In addition to reliability, the adoption of renewable sources can reduce operational costs and pollutant gas emissions, aligning with climate change mitigation goals. The decentralization of the system also enables the creation of cooperative generation arrangements, in which residents or community associations assume a leading role in the management and rational use of energy.

However, the effective integration of these technologies requires adequate technical planning, initial investment, and training of the communities involved.

Hybrid models that combine different sources and adapt to local characteristics have proven more efficient in overcoming the limitations imposed by environmental, regulatory, and economic factors.

Success Stories and Case Studies

Case studies documented in the literature demonstrate that the implementation of microgrids in vulnerable urban areas can generate positive results, provided they are adapted to local conditions.

In communities with limited infrastructure, microgrids have been employed as an alternative to ensure a more dependable, accessible, and sustainable energy supply [6]. Such experiences have contributed to broadening the debate on energy justice and social innovation.

In Brazil, initiatives such as those developed in isolated communities in the Amazon show that the adoption of hybrid solar microgrids can favor energy supply in hard-to-reach regions, reducing dependence on diesel generators and operational costs [4].

These projects involved community arrangements, institutional partnerships, and continuous technical support, factors that enabled their execution and maintenance.

In South Africa, experiences conducted in urban settlements demonstrate that the combination of solar energy with small-scale storage systems has the potential to meet basic residential demands, while fostering social participation and the development of local micro-enterprises [7].

The direct involvement of residents in planning and management was a differential for the acceptance of technology.

In Bangladesh, programs financed by international organizations enabled the installation of solar microgrids in rural and peri-urban areas, promoting significant improvements in health, education, and local productivity.

The replication of these models requires technological and institutional adaptation, according to the specificities of each territory [9].

These cases illustrate that, although promising, microgrids demand implementation strategies sensitive to the socioeconomic, environmental, and political context.

The success of projects is often related to the articulation between communities, local governments, the private sector, and financing agents.

Thus, the analyzed case studies reinforce the need for integrated approaches, with active community participation and continuous technical support, as a path to consolidate energy justice in vulnerable populations.

Materials and Methods

This study adopts an exploratory and descriptive approach, based on a literature review and analysis of case studies. The research was conducted using high-impact scientific databases, such as Scopus and Web of Science, employing key terms such as "energy justice," "microgrids," "urban vulnerability," and "renewable energy." The selection of articles followed the principles of the PRISMA protocol (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), as shown in Figure 1.

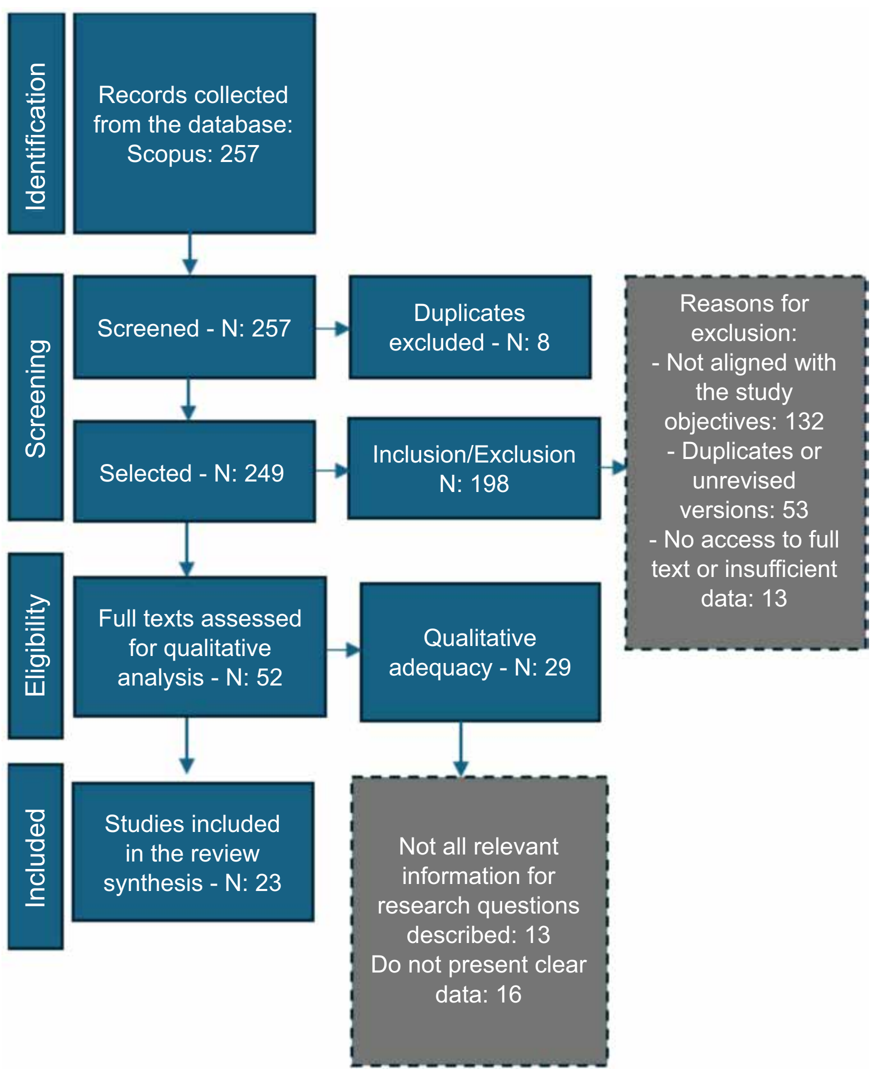
The methodological process included:

(i) identification of studies through systematic search;
(ii) screening of titles and abstracts;
(iii) selection of full-text articles based on inclusion criteria; and
(iv) analysis of the extracted data.

Priority was given to articles published in the last five years, focusing on empirical studies, systematic reviews, and theoretical works related to the intersection between energy justice and microgrids. Duplicate articles or those not directly aligned with the research objectives were excluded.

The qualitative analysis of the full texts followed the thematic content analysis technique, as proposed by Babalola, Daramola, and Iwarere [2], based on the categorization of extracted data into themes such as: social impacts, technical and economic feasibility, community participation, and public policies.

Figure 1. Flowchart of the study selection process.



This approach allowed the identification of patterns, gaps, and recurring contributions in the reviewed studies, enabling a critical discussion aligned with the research objectives.

The integration of systematic review with qualitative analysis aimed to ensure that the study's findings were applicable to real-world contexts, sensitive to sociocultural specificities, and capable of supporting the formulation of public policies and innovative practices.

Results and Discussion

The analysis of the literature and case studies selected through the PRISMA methodology revealed that microgrids represent a promising alternative to address the challenges of energy access in vulnerable urban areas. Although the results are qualitative, the data collected indicate significant impacts across social, economic, and environmental dimensions. Table 1 presents a summary of the main impacts identified in the literature, organized by dimension and accompanied by the respective references.

The inclusion of quantitative indicators strengthens the findings. As shown in Table 1, microgrid projects have demonstrated tangible results: in Brazil, up to 300 households benefited from hybrid solar systems [4]; in India, energy supply increased from 8 to 24 hours daily [14]; and in South Africa, schools and health posts gained reliable electricity [7]. Economically, families reduced their bills by 20–40% [2], projects created 10–20 local jobs [5], and surplus energy generated revenues of up to US$ 15,000 annually in Bangladesh [9]. Environmentally, hybrid systems avoided up to 120 tons of CO_2 per year in the Amazon [11], while increasing the share of renewables to 70% in some communities [4,7] and reducing technical losses by 15% [11]. These figures reinforce the qualitative evidence, providing more robust support for the conclusions.

Based on these impacts, it is possible to deepen the discussion of qualitative evidence related to each dimension.

In the social dimension, several studies indicate that the implementation of microgrids contributes to strengthening community autonomy, access to basic services, and improving quality of life [1,5]. In projects carried out in Latin America, for example, communities began to have stable energy supply for schools, health posts, and public lighting, which enabled significant improvements in local daily life.

However, social benefits do not materialize uniformly. The literature highlights that the success of such initiatives strongly depends on community engagement, the existence of local leadership, and the capacity to maintain the systems in the long term [9]. In some contexts, the lack of technical training and adequate governance models compromised the continuity of operations.

From the economic perspective, the cases analyzed suggest that microgrids can reduce

Table 1. Impacts of microgrid implementation in vulnerable urban areas.

Dimension	Main Impacts	Indicators	References
Social	Quality of life, energy poverty reduction, community resilience	300 households served (Brazil); supply increased 8h→24h (India); schools and health posts benefited (South Africa)	[1]; [4]; [9]
Economic	Cost reduction, jobs, entrepreneurship	−20–40% energy cost; 10–20 jobs/project; annual revenue up to US$ 15,000 (Bangladesh)	[2]; [5]; [14]
Environmental	GHG reduction, efficiency, renewables	−120 tCO_2/year (Amazon); renewables up to 70% of matrix; −15% technical losses	[4]; [11]; [14]

electricity costs for families and local enterprises, especially when power is generated from renewable sources and storage technologies are used [5]. Additionally, job creation in the implementation, operation, and maintenance stages has the potential to boost the local economy. However, high initial costs and the lack of accessible financing lines remain significant barriers [5].

In the environmental dimension, the replacement of fossil sources with solar or wind energy contributes to the reduction of greenhouse gas emissions and improves air quality [7,11].

The decentralization of generation and the use of storage reduce transmission losses and increase energy efficiency. Despite these advances, studies warn that improper battery and waste management may represent new environmental challenges [11].

It is important to emphasize that, although the benefits are recurrent in the experiences analyzed, microgrids do not constitute a universal solution. Their effectiveness is conditioned by the political, institutional, and cultural context of each community. Some authors point out that without public incentive policies, proper regulation, and continuous technical support, projects tend to lose momentum over time [14].

The convergence between the results obtained and the specialized literature reinforces the need for integrated and participatory approaches involving governments, the private sector, universities, and the community itself.

In this context, it is essential to develop methodological strategies that promote dialogue between technical-scientific knowledge and local knowledge, ensuring the adequacy of energy solutions to socio-territorial realities and strengthening the sustainability of interventions.

Conclusion

This study demonstrated that microgrids are an essential tool for mitigating inequalities in access to energy in vulnerable urban areas. Based on a systematic literature review and analysis of case studies, it was identified that the adoption of these systems can generate significant social, economic, and environmental benefits.

From a social perspective, microgrids not only improve the quality of life and strengthen community resilience but also deliver measurable results, such as providing reliable electricity to up to 300 households in Brazilian communities, expanding daily supply from 8 to 24 hours in Indian villages, and ensuring stable energy access to schools and health posts in South Africa.

In the economic dimension, projects have led to reductions of 20–40% in household electricity costs, the creation of 10 to 20 local jobs per initiative, and additional revenue of up to US$ 15,000 annually through the sale of surplus energy, as observed in Bangladesh. These figures highlight the potential of microgrids not only to reduce poverty but also to stimulate local entrepreneurship and strengthen community autonomy.

From an environmental standpoint, hybrid renewable systems have proven effective in avoiding up to 120 tons of CO_2 emissions annually, increasing the share of renewables in the local energy mix to nearly 70% in some communities, and reducing technical losses by approximately 15%. These quantitative indicators reinforce the role of microgrids in advancing climate goals and promoting sustainable urban development.

Despite these advances, the realization of benefits still requires overcoming significant barriers related to high initial costs, technological complexity, and regulatory challenges. The success of microgrid projects depends on active community participation, the presence of public incentive policies, and the provision of continuous technical support.

The integration of qualitative insights with quantitative evidence in this study strengthens the validity of the findings and provides a more solid foundation for policymaking. Future research is recommended to further expand the quantitative analysis of microgrid impacts and to develop replicable models adaptable to diverse urban contexts. By combining technical feasibility with social and environmental justice, microgrids emerge as a viable pathway toward a fairer, more resilient, and sustainable energy future.

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Scene Classification in Rural Environments for Autonomous Driving Using U-Net and ResNet

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This paper addresses the semantic segmentation of road images, a critical task for autonomous vehicle navigation, particularly in non-urban environments that present significant challenges. While much research focuses on well-maintained roads in developed countries, this study confronts the complexities of real-world conditions, such as those prevalent in developing nations, which feature vast networks of unpaved and poorly maintained roads. The core of our methodology is a neural network architecture that synergistically combines the encoder-decoder structure of U-Net with the feature extraction power of a ResNet backbone. The primary objective is the precise classification of each image pixel into one of four essential categories for navigation: background, asphalt, paved, and unpaved road. The model's training regimen involved exploring different ResNet versions (ResNet18, ResNet34, and ResNet50) as the encoder backbone to assess the impact of network depth. A key aspect of our approach was a progressive training strategy, where model versions were trained on images of varying resolutions. The results demonstrated a significant and somewhat counter-intuitive finding: training the ResNet34-U-Net model with images at half the original resolution yielded the best overall performance, achieving the highest Dice and IoU scores. This suggests that reducing image resolution acts as an effective form of regularization, compelling the model to learn more general and robust features by ignoring minor, irrelevant details. This outcome not only enhances the model's generalization capabilities for diverse and imperfect road conditions but also carries a substantial practical advantage by reducing the computational cost of training and inference, a crucial factor for deployment on resource-constrained embedded systems in autonomous vehicles.
Keywords: Semantic Segmentation, Computer Vision, Neural Networks, Rural Roads

Detecting a navigable path is an important function in visual navigation systems, where several challenges must be considered, such as terrain variations, lighting changes, and the presence of potholes or water puddles. Data from the National Transport Confederation of 2022 [1] show that only 15.81% of the Brazilian road network consists of paved roads, highlighting the challenge for the widespread adoption of autonomous vehicles in regions distant from large urban centers. Studies of this kind often utilize road scenarios from developed countries, which typically exhibit little to no variation in terrain surface [2]. Some works involve systematic literature reviews: for instance, one 11-year review analyzed computer vision methods applied to this type of problem, emphasizing the surface types these methods address, their adaptability to surface changes, and their capability to distinguish potential road defects or changes, such as potholes, shadows, and water puddles [3]. Convolutional Neural Networks (CNNs), the U-Net architecture, and Residual Networks (ResNet) have emerged as prominent deep learning architectures employed in this context. Research has primarily focused on improving semantic segmentation accuracy, acknowledging the ongoing challenges in achieving reliable environmental perception under diverse and complex driving conditions [4]. Convolutional Neural Networks (CNNs) represent a class of deep learning models whose fundamental architecture comprises convolutional layers, pooling layers, and activation functions. Convolutional layers act as feature extractors, learning hierarchical spatial patterns in the input data through the application of convolutional filters [4]. Pooling layers are responsible for reducing the spatial dimensionality of feature maps, providing translational invariance and decreasing sensitivity to minor input perturbations. Activation functions,

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such as ReLU (Rectified Linear Unit), introduce nonlinearity into the model, enabling it to learn complex relationships within the data [5]. As show in Figure 1, the U-Net is a convolutional neural network architecture characterized by its encoder-decoder structure.

The architecture consists of a contracting path (encoder) and an expanding path (decoder). The contracting path follows the typical CNN architecture, comprising multiple convolutional layers followed by max-pooling layers. These progressively reduce the spatial resolution of the feature maps while increasing the number of feature channels. This process allows the encoder to capture high-level contextual information from the input image [5]. Residual Networks (ResNets) address the vanishing gradient problem that typically hinders the training of very deep networks [6]. The main contribution of ResNet is the introduction of residual blocks, which employ skip connections or residual connections, as shown in Figure 2.

Instead of directly learning the underlying mapping, the layers within a residual block learn a residual function with respect to the block's input. This residual function is then added to the original input via the skip connection. These skip connections allow gradients to flow more directly through the network during backpropagation, facilitating the training of networks with hundreds or even thousands of layers [7].

Related Works

Semantic segmentation partitions an image into several semantically meaningful coherent parts and classifies each part into one of the predetermined classes. Existing semantic segmentation methods are unreliable for autonomous driving systems, as they ignore the differing levels of importance of distinct classes for safe driving. For instance, pedestrians, cars, and cyclists in a scene are far more critical than the sky or buildings, so segmentation must be as precise as possible. To incorporate the importance of object class information, the work present in [8] develops an "Importance-Aware Loss" (IAL), which emphasizes objects critical for autonomous driving. The IAL operates under a hierarchical structure where classes with varying importance are located at different levels, thus assigning a distinct weight to them.

Studies like [9] analyze semantic segmentation failures, which are crucial for autonomous driving systems, and detect failure cases in predicted segmentation maps by calculating the

Figure 1. U-Net network architecture [23]

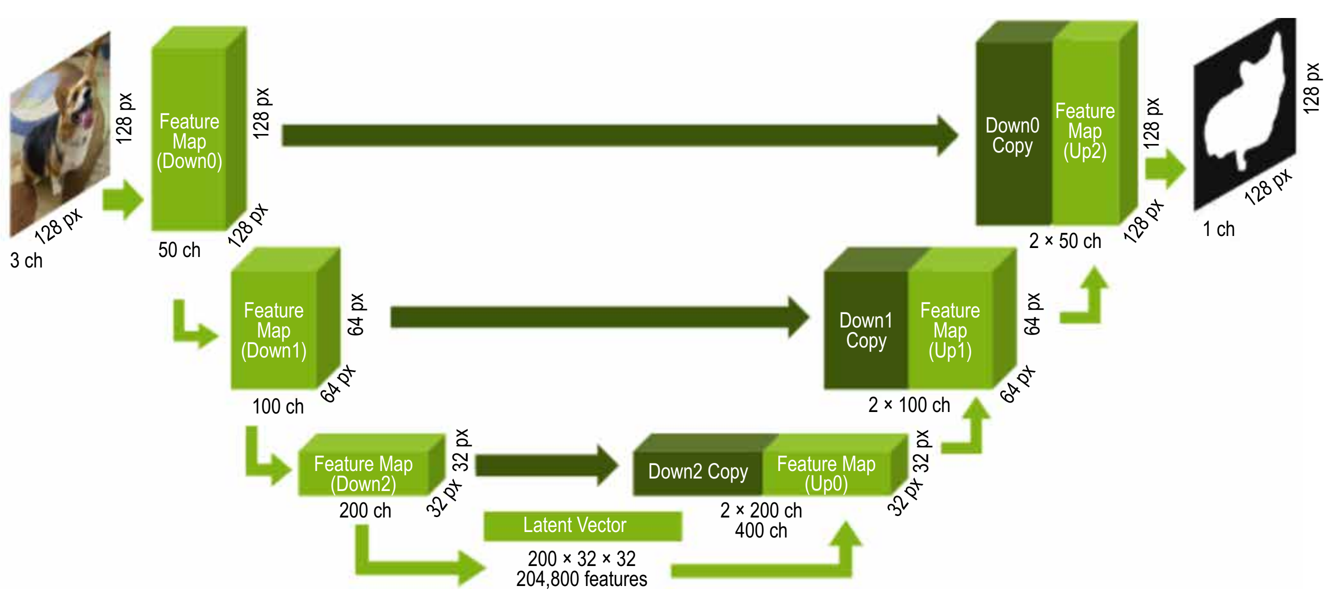
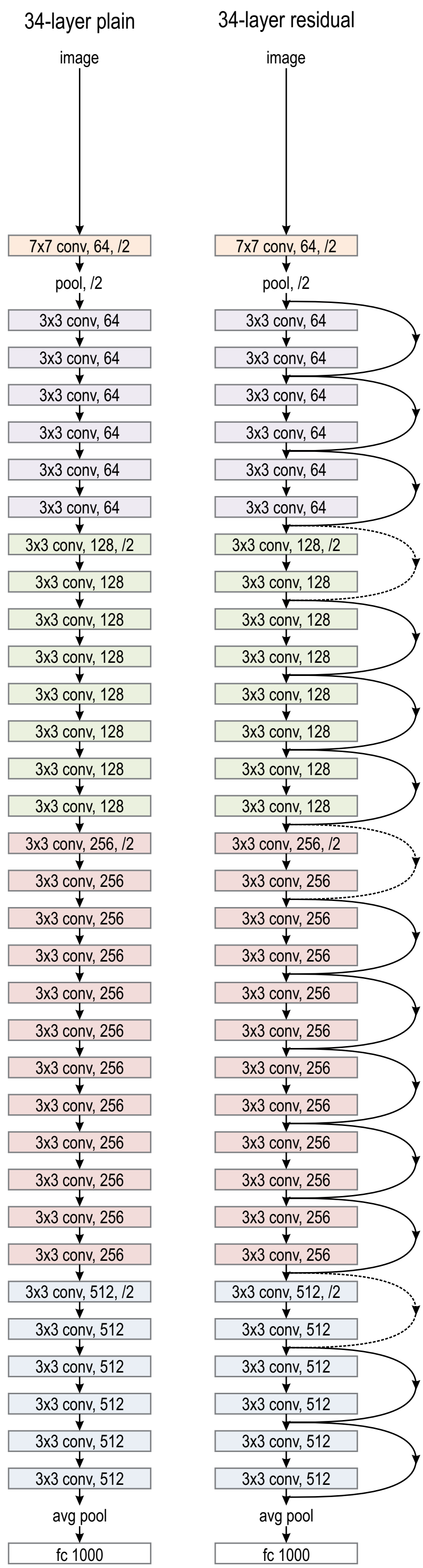


Figure 2. ResNet34 Network Architecture [7]



Mean Intersection over Union (mIoU). Authors developed a deep neural network to predict the segmentation map's mIoU without the ground truth, and introduced a new loss function to train on imbalanced data. Safety is an extremely critical factor in autonomous driving systems, where issues related to safety metrics for artificial neural networks [10], which are a type of artificial neuron architecture with functional similarities to biological neurons [11], have been extensively studied for semantic segmentation problems. The work presented in [12] categorizes road detection algorithms into three types considering different types of information: feature-based techniques, model-based techniques, and region-based techniques. Feature-based solutions are more effective, but they require roads with well-defined and easily identifiable markings; noise can disrupt the entire detection process. Model-based techniques are more robust; however, they are severely restricted by the geometry of the models. Region-based techniques use machine learning approaches, enabling them to handle noise problems and constant changes in the environment. Research has largely overlooked the problems posed by paved roads and roads with many potholes, as well as unexpected pavement interruptions, conditions commonly found in developing countries and even in certain parts of urban areas, such as city outskirts. For an autonomous vehicle to operate successfully, it must be able to handle these conditions during its operation. The work [13] presents road marking methods (lane detection), a system that is now integrated into Advanced Driver Assistance Systems (ADAS). This work also discusses how road models are represented, presents methods for feature extraction (e.g., image intensities, edge magnitudes and orientations, comparative models), and discusses whether any type of post-processing (e.g., Hough Transform) is employed. Although published in 2013, the work [14] reviews articles published only up to 2009, considering active vision sensors (LiDAR). The review also addresses the main challenges in road detection, such as weather and lighting conditions, the presence of shadows, other vehicles, people, or objects, and different road geometries. The work by [15] presents a review of articles published between 2005 and 2010 and also considers active vision sensors. It is a study focused on road detection, particularly lanes. Finally, authors in [16] presents work focused on road markings, concentrating on feature-based approaches like lane detection, stereoscopic analysis and edge-based segmentation.

Datasets for Autonomous Vehicle Navigation

Several benchmark datasets for road detection were analyzed: KITTI dataset by [17], CaRINA dataset by [18], CamVid dataset by [19], CityScapes dataset by [20], RTK dataset, and OffRoadScene dataset by [21]. One of the most widely used and cited datasets in path detection articles is the KITTI dataset, from the Karlsruhe Institute of Technology, Germany, featuring rural, urban, and highway scenarios. It presents situations with varying illumination. Most captures are on paved roads and it contains scenarios with many vehicles and pedestrians, as well as scenarios with little movement. For this work, the RTK dataset was used due to its well-curated road samples from Brazil, featuring different surface types such as asphalt variations, other types of pavements, and unpaved roads. It also includes situations with road damage (e.g., potholes).

Materials and methods

Dataset

The proposed method in this study addresses the semantic segmentation of road images using a neural network architecture that combines U-Net and ResNet. The objective is to classify each image pixel into one of the following categories: background, asphalt road, paved road, and unpaved road. The RTK dataset was used, which contains road images with different surface types and conditions. This dataset was chosen because it already has segmentation masks defined for each class, considerably reducing the time required for creating a database of images and segmentation masks. The dataset was divided into three parts: training, validation, and test, to evaluate the model's performance. This division was performed randomly, ensuring that each part represented the diversity of the original dataset.

Architecture

The U-Net network was combined with a ResNet backbone, which acts as an encoder to extract relevant features from the images. ResNet, proposed by researchers from Microsoft Research, uses residual blocks and skip connections to mitigate the vanishing/exploding gradient problem, enabling the training of deeper and more effective networks [22]. Different versions of ResNet (ResNet18, ResNet34, ResNet50) were explored as the model's backbone, allowing an evaluation of the impact of network depth on road segmentation.

Preprocessing and Data Augmentation

The images were resized to a standard resolution of 512 x 512 pixels, along with data augmentation techniques such as vertical and horizontal flips (at 90º), rotations (at 30º), and {zooms (at 2x). These transformations aim to increase the variability of the training data, making the model more robust to different lighting, orientation, and scale conditions.

Model Training

Model training was initially performed with ResNet18, using the three-cycle training strategy proposed by fast.ai. This technique involves training the model on progressive image resolutions (1:8, 1:4, 1:2, and 1:1) over three phases. This procedure aims to initially train general features and shapes, followed by object features, and finally, object textures. Learning was optimized using the fast.ai's fit one cycle method, which adaptively adjusts the learning rate and momentum. The learning rate was determined using the fast.ai learning rate find function, which helps identify the optimal learning rate for training. Finally, the loss function used was Cross Entropy Loss, suitable for multi-class classification problems, along with the Adam optimizer, known for its efficiency in training deep neural networks.

Evaluation Metrics

The model's performance was evaluated using the Dice and Jaccard metrics, which measure the similarity between the predicted segmentation masks and the ground truth masks. The Jaccard Coefficient, also known as Intersection over Union (IoU), is calculated as the ratio between the area of overlap and the area of union of the predicted and ground truth masks. The Dice metric is similar to IoU but gives more weight to true positives. In semantic segmentation tasks, the objective is to classify each pixel in an image, assigning it a label that represents the class of the object to which it belongs. To evaluate how well the model performs this task, metrics are used that compare the model's predicted segmentation with the actual segmentation (or ground truth).

In the context of image segmentation, these sets are the predicted segmentation mask (the model's output) and the ground truth segmentation mask. Mathematically, the IoU is defined as:

$$IoU = \frac{|A \cap B|}{|A \cup B|} \tag{1}$$

Where:

A represents the set of pixels belonging to a specific class in the predicted mask;

B represents the set of pixels belonging to the same class in the ground truth mask;

$|A \cap B|$ represents the number of pixels present in both A and B (the intersection);

$|A \cup B|$ represents the number of pixels present in A or in B or in both (the union).

The IoU measures the ratio between the area of overlap of the predicted and ground truth segmentations and the total area covered by both segmentations. An IoU of 1 indicates perfect overlap, while an IoU of 0 indicates no overlap.

The Dice metric, also known as the Dice Coefficient, is another commonly used metric to evaluate the similarity between two images. It is very similar to IoU, but differs slightly in its formulation:

$$Dice = \frac{2 \cdot |A \cap B|}{|A| + |B|} \tag{2}$$

Where *A, B,* $|A \cap B|$, $|A|$ and $|B|$ have the same meaning as in the IoU formula. The main difference between the Dice metric and IoU is that the Dice metric gives more weight to true positives (the correctly classified pixels. This is because the intersection is weighted twice as much, making it tend to be more sensitive to small details, and may be more appropriate when evaluating the segmentation accuracy of small objects.

Results and Conclusion

By comparing U-Net and ResNet architectures, as shown in Table 1, we demonstrated that the combination of a ResNet34 encoder with a U-Net decoder, trained on images at half the original resolution, yielded the best performance, achieving the highest Dice and IoU scores. This result indicates a robust capability for classifying pixels into essential categories such as asphalt, paved, and unpaved roads, as shown in Figures 3, 4 and 5.

The finding that a lower image resolution produced superior results is a significant outcome of this work. By decreasing the level of detail, the model is forced to learn more general and robust features of the road, minor texture variations, or irrelevant details in the vegetation. This not only improves the model's generalization capacity for varied and poorly maintained roads but also offers a considerable practical advantage: it reduces the computational cost of both training and inference, a critical factor for real-time application in embedded systems with limited processing power. Future work will be directed towards two main fronts. First, the cross-validation of the best-performing model (ResNet34 at 1/2 resolution) on a wider range of datasets to ensure its robustness and reliability under different conditions. Second, the

Table 1. Resolutions and performances.

Architecture	Resolution	Dice	IoU
ResNet18	1/8	0.615	0.607
ResNet18	1/4	0.641	0.615
ResNet18	1/2	0.654	0.633
ResNet18	1/1	0.655	0.634
ResNet34	1/8	0.616	0.610
ResNet34	1/4	0.635	0.610
ResNet34	1/2	0.656	0.635
ResNet34	1/1	0.636	0.615
ResNet50	1/8	0.622	0.619
ResNet50	1/4	0.643	0.618
ResNet50	1/2	0.646	0.625
ResNet50	1/1	0.650	0.630

Figure 3. Results for paved road

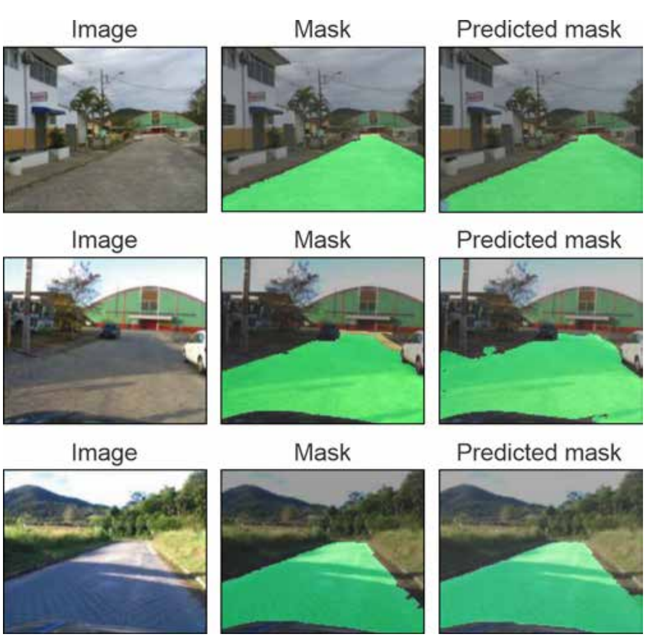


Figure 4. Results for paved and unpaved road

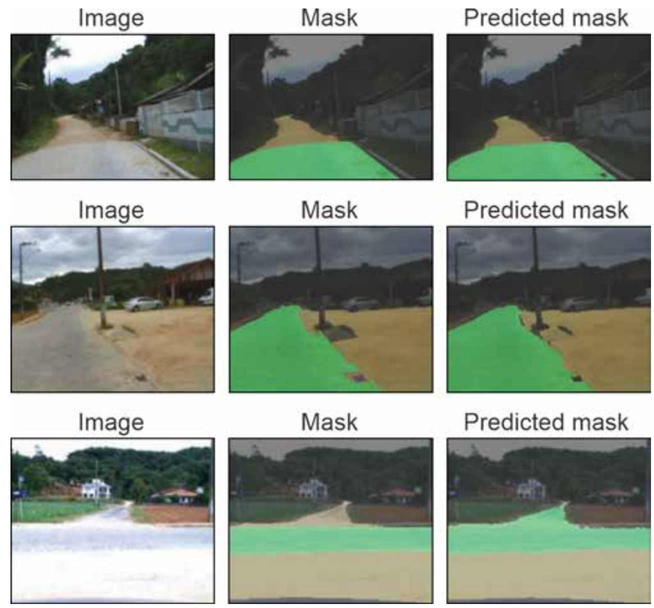
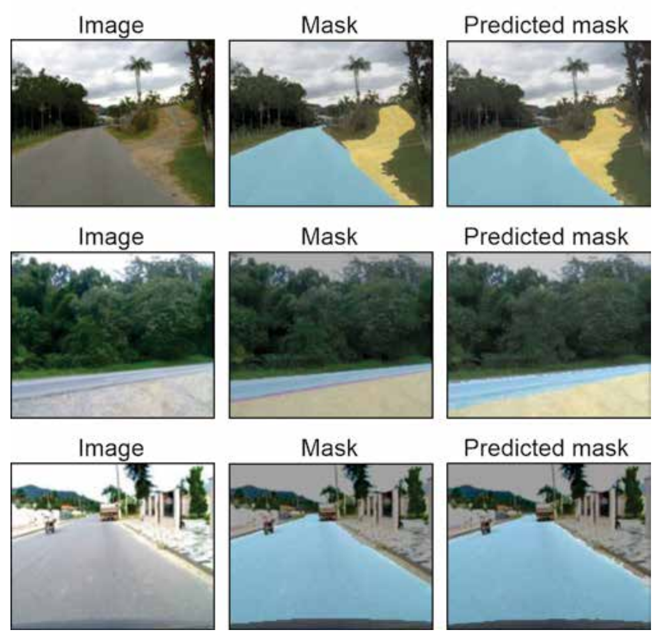


Figure 5. Results for asphalt and unpaved road



optimization of the architecture for deployment on embedded hardware, seeking a balance between accuracy and inference speed. As discussed in the literature, for safety-critical systems, understanding when the model is uncertain or likely to fail is as important as its accuracy. Implementing techniques to predict segmentation failures could significantly increase the safety and reliability of the autonomous navigation system, bringing it closer to practical and widespread use in challenging environments like those found in Brazil.

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Comparative Analysis of Functional Verification Strategies for RISC-V with Potential Use in CV-QKD Systems

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With the advancement of quantum computing, traditional cryptographic algorithms have become vulnerable, demanding solutions based on physical principles, such as continuous-variable quantum key distribution (CV-QKD). One of the main challenges for the practical adoption of CV-QKD lies in the digital signal processing (DSP) and post-processing stage, which imposes strict requirements for performance, reliability, and robustness against noise and faults. In this context, architectures based on the open fifth-generation Reduced Instruction Set Computing (RISC-V) standard have proven promising for building application-specific instruction set processor (ASIP) and specialized system-on-chip (SoCs), due to their flexibility, customization capabilities, and growing support ecosystem. However, ensuring the functional reliability of such systems requires the application of rigorous verification processes. This paper presents a comparative study of four complementary functional verification approaches: modular block-based verification, instruction-level transaction-based verification, black-box verification, and cycle-by-cycle comparison. Each approach was evaluated in terms of coverage, implementation complexity, and fault visibility. The study also highlights how these methods complement each other when applied in layered verification environments. The results show that no single approach can efficiently meet all requirements. High-level strategies are better suited for integration testing and broad functional validation, while low-level techniques are essential for localized debugging and precise timing analysis. This reinforces that verification success relies more on strategic integration than on a single optimal method. The findings indicate that adopting hybrid, layered solutions provides better scalability, supports regression testing, and improves both coverage and alignment with the security and performance goals required by CV-QKD systems.
Keywords: CV-QKD. RISC-V. Functional Verification. UVM. Digital Design.

With the ongoing advancement of quantum computing, traditional cryptographic algorithms such as Rivest-Shamir-Adleman (RSA) and elliptic curve cryptography (ECC) are expected to become insecure, requiring new secure communication paradigms such as CV-QKD, which guarantees security based on the laws of quantum physics [1,2]. However, the high-speed DSP and intensive post-processing steps represent a bottleneck in the practical implementation of CV-QKD [3-6].

The use of RISC-V instruction set architecture (ISA) [7], due to its customizable and open-source nature, enables the development of ASIP and SoCs optimized to accelerate these DSP and postprocessing tasks [8-10]. However, to ensure the reliability of such systems, robust functional verification of the RISC-V core is essential, presenting a complex challenge due to the presence of pipelines, complex sequential logic, and temporal dependencies.

To manage this verification complexity, different methodologies exist [11,12], among which the Universal Verification Methodology (UVM) is commonly adopted [13-15]. UVM enables the creation of scalable and reusable verification environments across different levels of abstraction [16,17]. As shown in Figure 1, which illustrates a standard structure UVM testbench environment, each component has a specific function and can be reused or extended according to verification needs. In the RISC-V context, UVM enables hybrid verification strategies, combining internal signal analysis with input-output (black-box) based tests [18-20].

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This work presents an initial-stage comparative study of four verification approaches applied to a basic RISC-V implementation, aiming to evaluate the trade-offs between abstraction level, verification visibility, and methodological complexity. The approaches investigated — ranging from modular testing to clock-cycle-accurate comparison — provide foundational insights into their respective strengths and limitations. While this study serves as an early investigation, its conclusions are designed to inform and guide the selection of optimal verification strategies for the development of more complex, security-dedicated ASIPs and SoCs for CV-QKD DSP and postprocessing. The ultimate goal is to establish a robust verification methodology that ensures functional reliability in future high-performance, realtime systems where any flaw could compromise cryptographic integrity.

Materials and Methods

During the development of functional verification, various strategies were explored, each operating at a different level of abstraction. The approaches evaluated included modular block-based verification, instruction-level transaction-based verification, black-box verification, and cycle-by-cycle verification. These strategies support the development of unit testing within the context of hardware verification, enabling their application to both individual components and complete system implementations through the isolated analysis of specific design elements. The following sections provide a detailed description of each strategy.

Block-Level

Verification This technique involved the isolated verification of individual processor components such as the arithmetic logic unit (ALU), decode unit, comparators, and multiplexers [22]. Stimuli were applied directly to the inputs of these blocks, and the outputs were monitored to verify compliance with the expected behavior. Tests were implemented using simple testbenches and could be complemented with internal SystemVerilog assertions (Figure 2).

Transaction-Based Verification

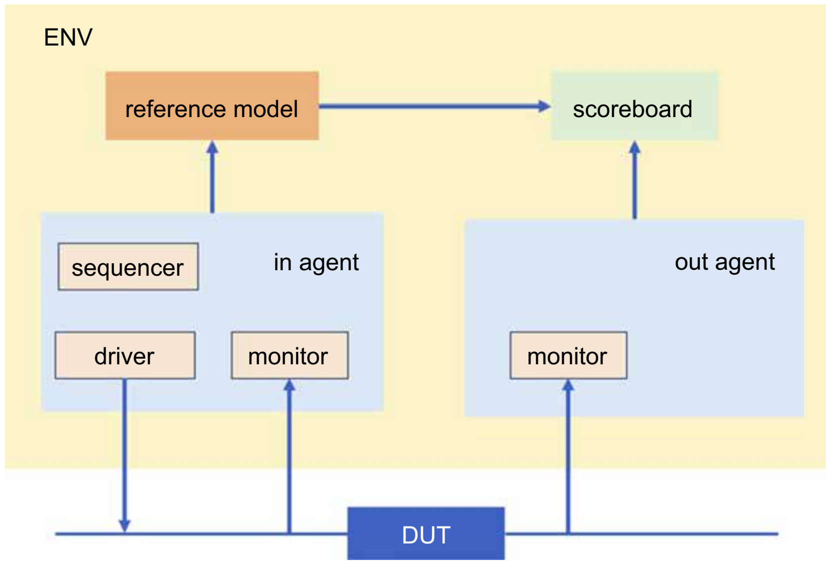
This approach focused on verifying individual instructions in isolation. In this setup, a single instruction was sent to both the processor and the reference model over a specific number of clock cycles, depending on the processor's latency. The reference model processed the instruction instantaneously, while a monitor captured the processor’s response after the natural pipeline latency. The output signals were then compared against the results produced by the reference model (Figure 3).

Black-Box Verification

In this strategy, instruction sequences were composed of LOAD operations, intermediate instruction set operations, and concluding STORE instructions [23]. Registers were initialized with known values, and the final data written to memory was used for verification. No internal signals were monitored; evaluation was based solely on observable results after program execution. This approach is particularly useful in scenarios where internal signals – such as ALU outputs or intermediate data – are not externally accessible. This is especially relevant in the context of RISC-V, where there is no official hardware implementation, only an ISA specification [7].

Different cores may expose or conceal internal signals in various ways, as discussed in Oleksiak and colleagues [18]. Verification at this level of abstraction is therefore highly reusable across different RISC-Vcompliant implementations, representing the most generic form of functional verification. This approach is also inherently robust to pipeline and timing variations, as checking is performed only after execution has completed (Figure 4).

Figure 1. Standard UVM environment setup.



Source: Liu and colleagues [21].

Figure 2. Block-level verification strategy.

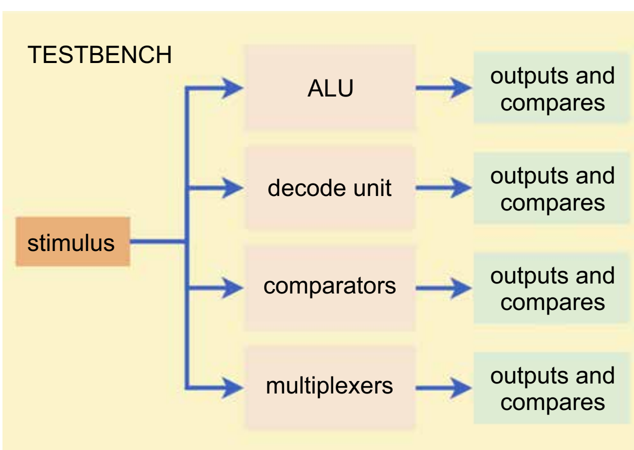


Figure 3. Transaction-based verification at the instruction level.

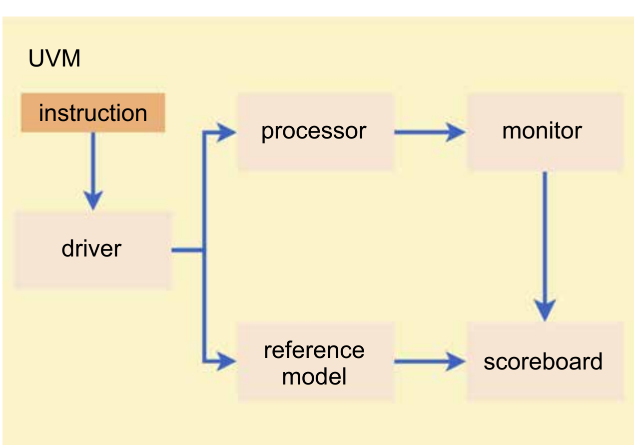
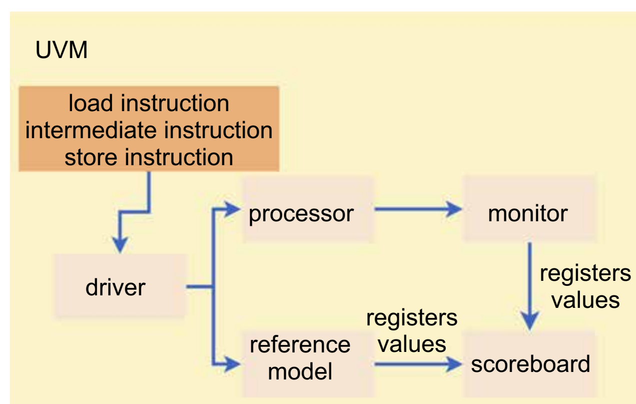


Figure 4. Black-box verification using memory output comparison.

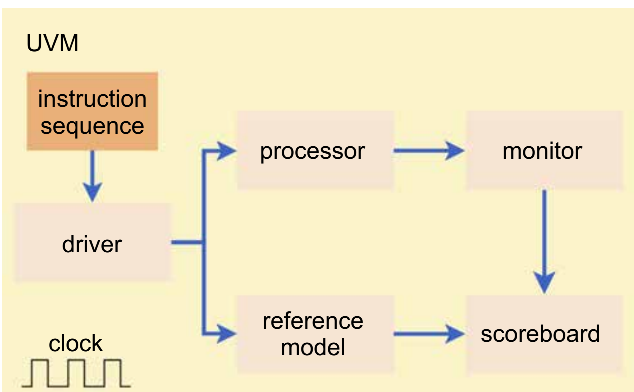


Cycle Accurate Verification (Clock Level)

This approach combined elements from the two previous strategies in a hybrid method. Instruction blocks were composed of LOAD operations, randomly selected arithmetic or logical instructions, and concluded with STORE operations, similar to the black-box strategy. However, in this version, internal signals – such as memory addresses, data to be written, and the instruction address (programCounter) – were monitored and compared on a cycle-by-cycle basis. These signals were also used as analysis parameters in Schiavone and colleagues [19]. To support this, the reference model was extended to simulate a complete processor, capable of handling stalls, forwarding, and other typical pipeline behaviors.

Although this approach is not fully generic across all RISC-V implementations, it enables precise cycle-by-cycle comparison of input and output signals for this specific processor. This strategy offers a balanced trade-off between observability and practicality, facilitating error identification and providing deeper insights into processor behavior (Figure 5).

Figure 5. Cycle-accurate verification with internal signal monitoring.



Results and Discussion

Throughout the verification of the RISC-V processor, each of the previously described approaches was applied at different stages of the project. This section presents the main results observed for each strategy, along with the practical challenges encountered during their implementation.

Modular Verification

Modular verification proved to be highly effective in identifying localized faults and providing an initial validation of the core modules before full processor integration. It exhibited low implementation complexity, reduced development time, and facilitated debugging. However, it does not cover the integration between components, timing effects, hazards, or complex sequential behavior typical of processor pipelines, thus limiting its applicability in global behavior testing.

Instruction-Level Transactional Verification

The transactional approach enabled effective analysis of simple instructions by comparing the output signals of the device under test (DUT) with those of the reference model, and it facilitated the detection of decoding errors. However, it presented difficulties with instructions that affect control flow or require forwarding, such as BEQ and JAL. The absence of mechanisms to indicate execution completion required the manual insertion of NOP instructions, making the approach timingsensitive and unstable in complex scenarios. Although initially promising due to its ability to perform targeted validations with good granularity, the approach proved unreliable in tests involving execution dynamics, such as branches, stalls, or paths with forwarding, compromising its effectiveness in realistic environments.

Black-Box Verification

The method proved simple and robust for basic programs. Since it did not rely on the internal timing of the DUT, it avoided synchronization issues. However, its low observability hindered fault diagnosis, requiring artificial mechanisms to identify the end of program execution. While advantageous in eliminating timing-related concerns, this approach is not suitable for validating temporal aspects of the design – such as the number of cycles required to execute a program or the behavior under conditions like forwarding and stalls. In such cases, complementary verification methods are essential.

Cycle-by-Cycle Verification

The most fine-grained approach provided the highest functional coverage among the methods, enabling the detection of subtle mismatches. However, it was extremely sensitive to desynchronization between the DUT and the model, requiring strict alignment of signals such as clock and reset. The complexity of the reference model and the comparison infrastructure increased significantly, including the need to simulate pipelines, stalls, forwarding, and other timing effects. This approach proved viable only in scenarios where synchronization could be maintained with precision.

Comparative Analysis of Verification Methods

To summarize the advantages and limitations of each verification approach, Table 1 presents a comparative analysis based on key evaluation criteria. The analysis shows that no single method is optimal for all verification needs. Modular verification is most effective during the early stages of development, while black-box techniques offer the highest reusability. For comprehensive validation, cycle-by-cycle verification provides the most detailed insights, despite its implementation complexity. An effective verification strategy should combine these methods according to the specific requirements and phase of the project.

Discussion

This section examines the key considerations and trade-offs involved in the verification of digital systems. Different strategies offer varying levels of coverage, complexity, and maintainability. By analyzing specific aspects such as levels of abstraction and regression testing, we aim to highlight practical insights and common challenges encountered during functional verification.

The Core Trade-off: Abstraction, Coverage, and Complexity

The results reveal a clear trade-off between coverage and complexity, which is directly influenced by the chosen level of abstraction. Low-level techniques, such as cycle-by-cycle verification, provide detailed visibility but are sensitive to small design changes and can be difficult to maintain. In contrast, block-level tests and high-level methods like black-box verification are simpler and more robust to internal modifications, but they offer limited coverage, making it more challenging to locate and diagnose functional failures. Validating modules such as ALUs or decoders in isolation enables early bug detection and serves as a foundation for more complex validations. Ultimately, the appropriate level of abstraction depends on the project phase, available resources, and the types of errors being targeted. Hybrid strategies that combine multiple levels often provide the best balance between verification effort and coverage.

Functional Verification Is Not Complete Verification

Even when a design passes directed tests and incorporates techniques such as random testing, assertions, and coverage analysis, it may still contain latent bugs. Functional verification, although comprehensive in scope, is inherently

Table 1. Comparison of verification methods.

Criteria	Modular	Transactional	Black-Box	Cycle
Implementation Complexity	Low	Medium	Low	High
Level of Debugging	High	Medium	Low	Medium
Timing Sensibility	None	High	None	Very High
Reusability	Low	Medium	High	Low
Reference Model	Simple	Medium	Simple	Complex

limited by the scenarios it can realistically cover. Rare corner cases or complex interactions may go undetected. Therefore, achieving complete verification requires combining multiple strategies – including formal methods and runtime validation – to minimize the risk of undetected failures and increase overall design confidence.

The Importance of Regression Testing

Design changes can introduce regressions in previously stable functionalities. A comprehensive set of regression tests is essential to ensure system integrity over time. Automation and continuous integration are key to detecting new bugs efficiently, as demonstrated by [24], where cron jobs and Bash scripts were used to run regressions automatically.

Conclusion

This study presented a comparative analysis of four functional verification strategies for a basic RISC-V core, demonstrating that no single approach is universally optimal. Instead, effective verification relies on a multi-layered strategy that combines high-level functional tests with lowlevel, cycle-accurate debugging, with the choice of technique involving a clear trade-off between abstraction, visibility, and complexity.

For security-critical applications such as CV-QKD DSP and post-processing, this rigorous, multifaceted verification is a fundamental requirement to ensure reliability. The insights and guidelines derived from this work provide a practical foundation for selecting and integrating verification strategies in the development of more complex, dedicated RISC-V ASIPs and SoCs, where the intelligent combination of these complementary techniques will be critical to success.

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Christmas Tree Market Analysis for the Upstream Oil and Gas Sector

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The oil and gas sector is central to the global economy, providing both energy inputs and industrial raw materials. Within the upstream segment, a critical piece of equipment stands out: the "Christmas tree," a robust assembly of valves and fittings installed at the wellhead of producing wells to regulate hydrocarbon flow. This study maps the commercial dynamics and supply strategies of major global operators (Saudi Aramco, CNPC, ExxonMobil, and Chevron) in relation to their Christmas tree suppliers. The methodology consisted of a broad literature review, including the analysis of corporate and technical reports from 2003 to 2025, as well as publications from oil and gas business platforms. The findings reveal a heterogeneous and strategically structured network of commercial interactions. Saudi Aramco maintains strong, long-term relationships with suppliers such as Dril-Quip and TechnipFMC, which develop surface and subsea Christmas tree models tailored to the specific requirements of its projects. In a distinct approach, CNPC diversifies its supplier base by prioritizing domestic manufacturers such as BOMCO, Sanjack Petro, and Cepai, integrating solutions that include horizontal subsea equipment. Conversely, ExxonMobil and Chevron converge on a multilateral approach, establishing long-term contracts with the three largest global suppliers: TechnipFMC, SLB (OneSubsea), and Baker Hughes. These partnerships are characterized by the adoption of cutting-edge technologies, including Aptara™, Subsea 2.0™, and monobore configurations, all aimed at maximizing efficiency and operational safety. It is concluded that major upstream companies maintain a diversified supplier portfolio as a strategic cornerstone. The analysis demonstrates that supplier diversity reflects corporate policies focused on innovation, energy security, and, in some cases, the strengthening of local supply chains, thereby ensuring resilience and competitive advantage in the global landscape.

Keywords: Upstream. Oil&Gas. Tree Subsea. Commercial Relationship.

Among the sectors with the greatest relevance and robustness in the global economy, the oil and gas market stands out, being responsible for the supply of essential inputs such as natural gas and crude oil, as well as raw materials for the manufacturing of various products present in everyday life, including plastics, cosmetics, and asphalt. The production chain of this industry is traditionally segmented into three main stages: upstream, midstream, and downstream (Figure 1) [1].

The upstream stage constitutes the core of the oil and gas industry, encompassing exploration and production activities. In this phase, a wide range of technologies and equipment is employed to ensure an efficient and safe extraction process. Among these, the Christmas tree stands out, consisting of a set of valves and connections installed at the wellhead of producing wells located in both onshore and offshore environments [2]. There are two main models: the SCT (Surface Christmas Tree), which is conventional and located at the surface, and the SBT (Subsea Christmas Tree), installed on the seabed. Specifically, for the SBT, varying operational conditions lead to further subclassifications, related to the depth of the well in which they operate.

Brazil has focused on the manufacturing of subsea Christmas trees (SBTs), with SLB OneSubsea facilities located in Taubaté (SP) and Curitiba (PR). Investments in this sector underscore a strategic capability that enables safe and efficient access to pre-salt reserves [3]. Therefore, understanding the global specificities in the supply of surface Christmas trees (SCTs) and subsea Christmas trees (SBTs) is essential to align operations with established market dynamics and supply-related requirements.

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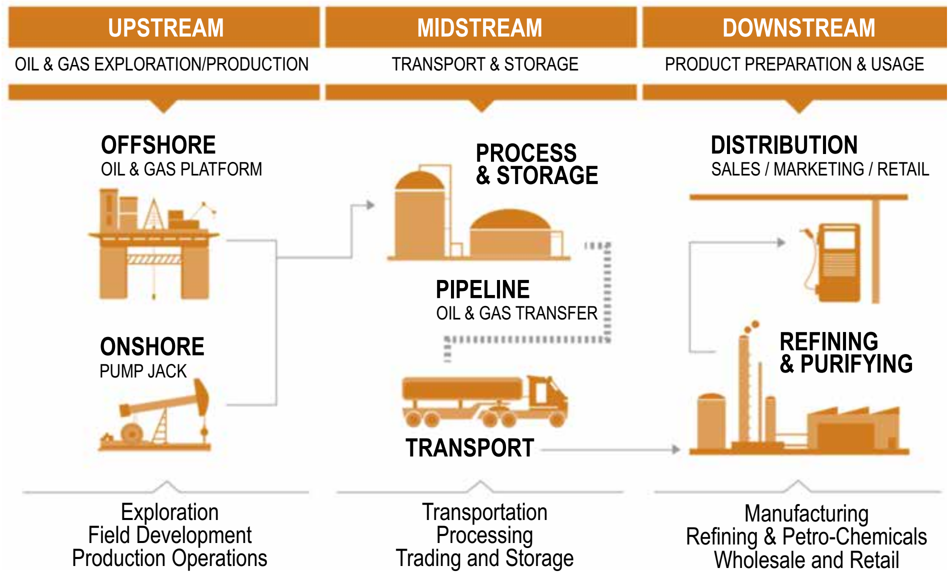
Figure 1. Diagram illustrating the stages of the Oil & Gas market.



Source: Eland (2025) [1].

From this perspective, the objective of this study is to analyze the interactions between major global oil and gas operators in the upstream segment and their main suppliers of Christmas trees, thereby elucidating the commercial and technological dynamics inherent to this strategic alliance.

Theoretical Framework

The Christmas tree is a sophisticated assembly of valves and fittings installed at the wellhead of production units, designed to regulate critical variables such as pressure and flow while ensuring operational safety during hydrocarbon extraction [4]. Two main models exist: the Surface Christmas Tree (SCT), employed in onshore and offshore platforms, and the Subsea Christmas Tree (SBT), deployed on the seabed for deepwater operations. The SBT, due to its technical complexity and high cost, represents a central element for the economic viability of pre-salt projects in Brazil as well as in other scenarios involving significant operational challenges [5]. The ability to design and manufacture this equipment domestically, as occurs in Brazil, reinforces its strategic importance by directly linking it to energy security and industrial competitiveness.

The Christmas tree market is characterized by a dense and complex network of interactions between operators and global suppliers, shaped by technological, strategic, and geopolitical factors that influence everything from supplier selection to the adoption of specific equipment models [6]. Each operator develops its own procurement strategy, seeking to balance efficiency, innovation, safety, and competitiveness.

Within this context, the analysis of commercial relationships demonstrates that the supply of Christmas trees transcends a purely transactional logic and assumes a strategic dimension. The equipment constitutes a central axis in the formation of global cooperation networks: suppliers rely on the capital resources and scale of operators to enable innovation, while operators depend on suppliers' technological expertise to access and exploit new reserves. This interdependence results in a system in which a small number of players concentrate control over the technological and commercial trajectory of the sector.

The main drivers of supplier diversification include technical robustness, risk mitigation, economic competitiveness, operational adaptability, incentives for innovation, and the strengthening of energy security. Thus, the upstream Christmas tree market emerges as a highly strategic arena, sustained by a global network of technological and commercial cooperation that goes beyond the mere supply of equipment and lies at the core of ongoing competition for innovation, efficiency, and safety within the oil and gas sector.

Through Figure 2, it is possible to observe the aspect that guided the selection of the companies to be addressed in this study.

The selected documents were categorized by company, and their information was transformed into spreadsheets and flowcharts that illustrate this commercial interaction.

Results and Discussion

This section is dedicated to the analysis of the key commercial relationships established between the corporations Chevron, Saudi Aramco, CNPC, and ExxonMobil, as identified throughout the investigation focused on the procurement of Christmas tree equipment. Furthermore, their respective global operating regions and corporate structures will be examined, crucial elements for understanding the dynamics of the market under consideration.

Saudi Aramco

Saudi Aramco operates in an integrated manner across more than 40 countries, consolidating its global presence in different segments of the energy sector value chain (Figure 3) [7].

Although publicly traded, Saudi Aramco remains largely controlled by the Saudi state, directly influencing its governance structure, corporate strategies, as well as investment decisions [8].

The commercial relationships established between Saudi Aramco and its Christmas tree suppliers have been concentrated on leading companies in the production technology sector, notably Dril-Quip and TechnipFMC [9]. Each supplier has contributed different technologies and Christmas tree models tailored to Aramco's operational needs in both onshore and offshore projects.

Although there are no public records explicitly detailing the specific type of Christmas trees acquired by Saudi Aramco, it is possible to associate the equipment types with the advanced technical features offered by these companies.

TechnipFMC provides a wide range of models, including surface Christmas trees — Conventional, Unihead®, and for shale formations — as well as subsea vertical and horizontal models, and equipment designed for high-pressure, high-temperature (HPHT) environments [10–11].

Dril-Quip, for instance, has developed both subsea and surface Christmas trees, notably the VXTe™ and SBTe™ models, which are widely recognized for their reliability and performance in deepwater operations [12–13].

Figure 2. Ranking of the four leading companies in crude oil production (2023–2024).

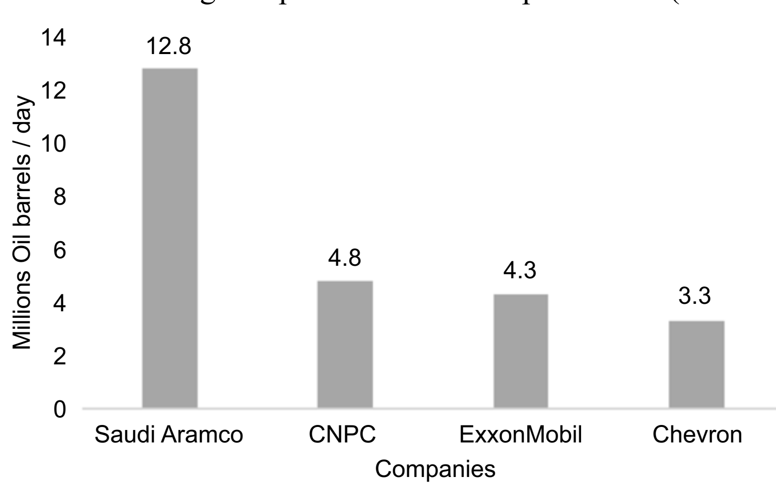
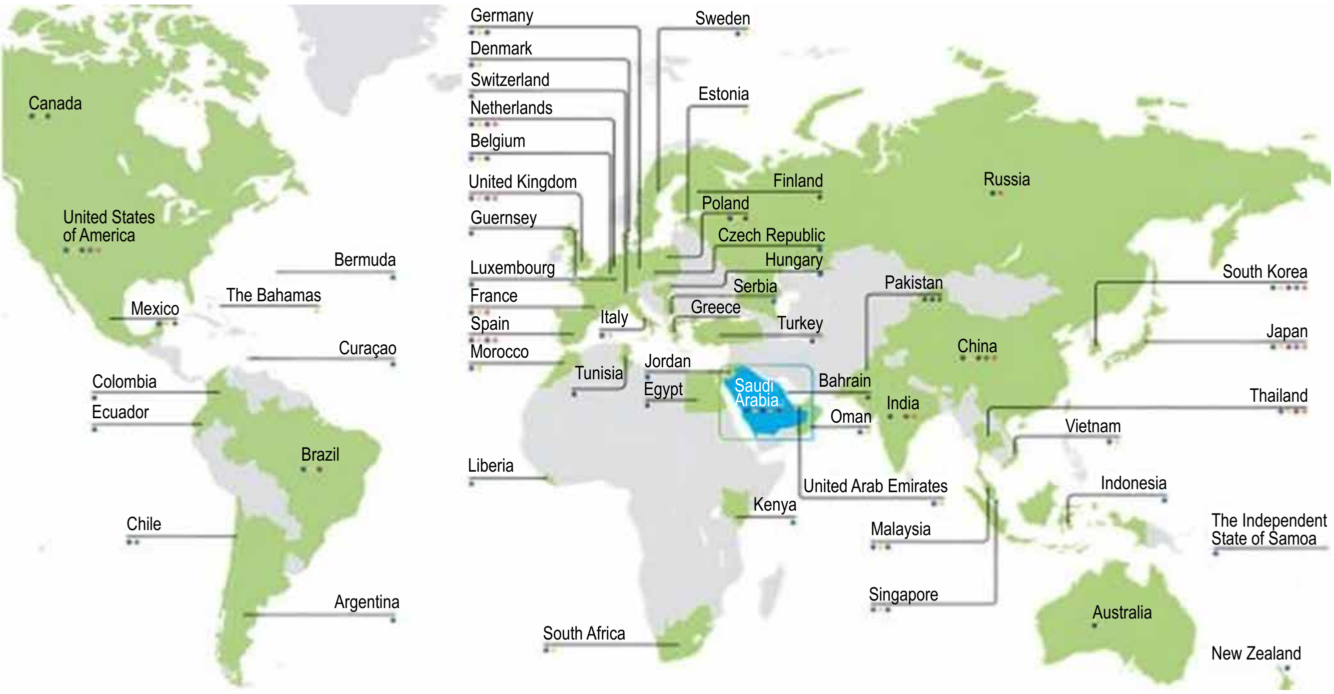


Figure 3. Geographical distribution of Saudi Aramco's operational units worldwide.



Source: Adapted Saudi Aramco (2024) [7].

<u>China National Petroleum Corporation (CNPC)</u>

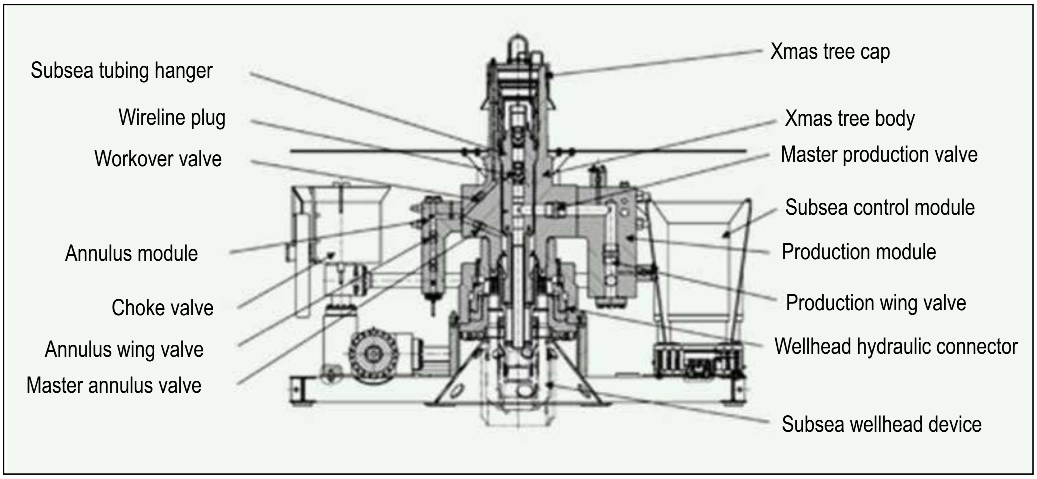
CNPC is a Chinese state-owned enterprise operating in more than 30 countries, with a broad portfolio ranging from oil exploration to refineries and natural gas supply [14] (Figure 4).

Over the past two decades, the China National Petroleum Corporation (CNPC) has incorporated a wide variety of Christmas tree models, reflecting the technological diversity available in the international market for both subsea and conventional applications. Among the identified suppliers, Baoji Oilfield Machinery Co. Ltd. (BOMCO) stands out for supplying horizontal subsea Christmas trees (Figure 5) [15].

Figure 4. Global map of CNPC operations in Oil & Gas exploration and production, oilfield services, and petroleum equipment manufacturing.

Source: CNPC (2024) [14].

Figure 5. Description of subsea horizontal christmas tree equipment.



Source: CNPC (2014) [15].

TechnipFMC has contributed with HXT (Horizontal Xmas Tree) and VXT (Vertical Xmas Tree) models, both designed for subsea operations [16]. In the conventional Christmas tree segment, within the supplier landscape, notable companies include Sanjack Petro, Cepai (Yulin Machinery), and Saintwah, whose products — in the case of the latter two — comply with API 6A specifications, an industry benchmark standard for the standardization of wellhead (surface) and downhole (subsurface) components [17–19].

<u>ExxonMobil</u>

ExxonMobil is a publicly traded company with global operations in more than 60 countries. Its activities encompass multiple integrated stages of the oil and gas industry value chain (Figure 6) [20].

ExxonMobil's acquisitions for the supply of subsea Christmas trees have been concentrated among TechnipFMC, OneSubsea (SLB), and Baker Hughes. TechnipFMC supplied the

Figure 6. ExxonMobil's global operations.

Source: ExxonMobil (2022) [20].

EVDT and Subsea 2.0® models [21–22], while OneSubsea (SLB) and Baker Hughes provided subsea Christmas trees without disclosed technical specifications [23–24]. The diversity of suppliers and models employed reflects ExxonMobil's strategy of adopting technology solutions tailored to specific operational environments and technical requirements.

Chevron

Chevron Corporation is a U.S.-based publicly traded company that operates in an integrated manner across the entire oil and gas industry value chain, covering upstream through downstream segments. The company maintains a significant concentration of exploration activities in North and South America (Figure 7) [25].

Over the past decades, Chevron has established and maintained strong commercial relationships with leading subsea equipment suppliers, including OneSubsea (SLB), TechnipFMC, and Baker Hughes. Baker Hughes supplied Aptara™ model Christmas trees [26]; TechnipFMC provided the Subsea 2.0™ system [27]; and OneSubsea (SLB) delivered vertical monobore production trees [28]. The diversity of suppliers and technologies adopted reflects Chevron's strategy of integrating advanced and modular solutions into the various operational conditions of its offshore assets.

Conclusion

Therefore, it can be concluded that the commercial dynamics of the upstream sector in the acquisition of Christmas tree equipment present an organized and strategic structure, in which major international companies maintain relationships with multiple suppliers. This diversity is shaped by factors such as specific exploration conditions, technological cooperation agreements, regional partnerships, and objectives related to local economic development, as well as alignment with each corporation's business model. As a result, a diversified and integrated commercial network is established, tailored to the operational and strategic demands of the sector.

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Figure 7. Chevron's global operations.

Source: Chevron (2021) [25].

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Biorefinery of Cocoa Waste: A Systematic Review and Bibliometric Analysis

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The growing demand for sustainable alternatives to produce biofuels and bioproducts has driven the development of biorefineries based on agro-industrial residues. Cocoa (*Theobroma cacao* L.), an important agricultural commodity, generates approximately 70–80% of residues during its processing, presenting significant potential for use in integrated conversion processes. This study presents a systematic literature review combined with a bibliometric analysis to answer the question: Do cocoa residue biorefineries exist? The literature search was conducted using the Scopus and Web of Science databases, resulting in the selection of 32 articles. The main publication trends, countries, journals, authors, institutions, and associated keywords were analyzed. The results show that scientific production on cocoa residue biorefineries is emerging, concentrated in cocoa producing countries in Latin America and Asia, and strongly related to bioenergy routes, bioactive compounds, and the circular economy. This analysis provides both quantitative and qualitative insights to support the development of biorefinery proposals and the identification of research gaps.
Keywords: Cacao Residues. Biorefinery. Bibliometric Analysis. Circular Economy. Sustainable Energy.
Abbreviations: Abbreviations: WoS, Web of Science; Scopus, Elsevier Scopus database; LCA, life cycle assessment.

The growing demand for sustainable solutions in energy and materials has driven efforts toward the development of biorefineries that use agro-industrial residues as feedstock. Cocoa (*Theobroma cacao* L.), an important agricultural commodity with significant production in Brazil, Ghana, and Côte d'Ivoire, generates approximately 70–80% of residues during its processing — including husks, pulp, and mucilage — presenting significant potential for use in integrated conversion processes [1].

These residues can be converted into bioethanol, biobutanol, biogas, and high-value-added compounds, thereby fostering the circular economy and contributing to CO_2 emissions mitigation [2,3].

This study aims to conduct a systematic literature review combined with a bibliometric analysis to address the central question: Do cocoa residue biorefineries exist? The quantitative analysis of the articles seeks to identify global trends, research gaps, and potential technological routes for cocoa residue valorization, while providing qualitative and quantitative evidence to support the development of integrated conversion processes and the identification of key opportunities in the field.

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Materials and Methods

This study was conducted in three sequential stages (Figure 1):

(i) Systematic search – Literature search in Scopus and Web of Science using predefined keywords (Table 1) to maximize coverage while ensuring topic relevance.

(ii) Filtering and bibliometric analysis – Publications were screened according to the adherence criteria. VOSviewer was used for keyword co-occurrence and co-authorship network mapping. Microsoft Excel was employed for data organization, statistical summaries, and generation of charts by country, journal, and other metrics.

(iii) Qualitative assessment – Selection of key articles, conversion routes, and products, with emphasis on studies providing data applicable to the simulation of cocoa residue valorization processes.

Adherence Criteria

- Publications written in English and available in full text.

Figure 1. Flowchart of the review and bibliometric analysis method.

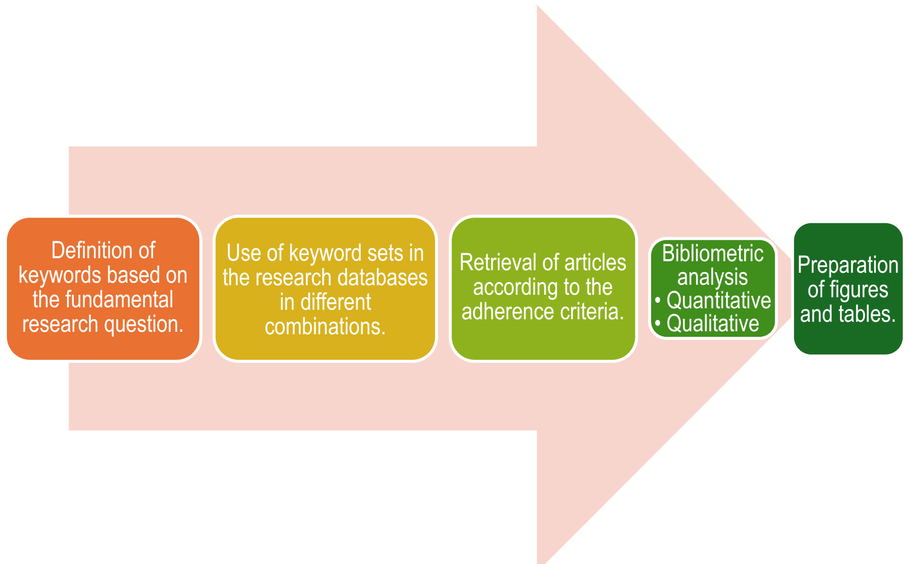


Table 1. Keyword sets used in the study.

Sets	Keyword Set
Set 1	(cacao OR cocoa OR "cocoa waste" OR "cocoa shell" OR "cocoa pod husk" OR "cocoa by-products" OR "cocoa residues")
Set 2	(biorefinery OR biorefining OR "biomass valorization" OR "bio-based refinery" OR "bioprocessing")
Set 3	("process simulation" OR "process modeling" OR "flowsheet simulation" OR "Aspen Plus" OR "SuperPro Designer" OR "process systems engineering")
Set 4	(cacao) AND (biorefinery) AND (process simulation)

- Publications falling into at least one of the following categories:
  - o Informational research
  - o Computational simulation
  - o Experimental study
  - o Data analysis
  - o Mathematical modeling
- Studies directly contributing to the central research question, i.e., providing data suitable for the simulation and assessment of cocoa residue valorization pathways.

The Scopus data analysis tools were used with Search 5 to generate, in some cases, selected graphs for the study.

Results and Discussion

The results section presents the main findings from the systematic review, along with the bibliometric and qualitative analyses, highlighting publication trends, research networks, and thematic focuses. These outcomes provide a comprehensive overview of the scientific landscape on cocoa residue biorefineries and identify potential opportunities for technological development.

The systematic review was conducted using the keyword combinations listed in Table 2. Initially, 34 documents were identified. One duplicate and one report or book chapter were excluded during the selection process, resulting in a final set of 32 articles.

Table 2. Literature search strategy.

No*	KSet*	WOS R*	AR*	SCO R*	AR*
1	Set 1	14.559	-	136.251	-
2	Set 2	23.018	-	293.610	-
3	Set 3	27.519	-	237.318	-
4	Set 4	4	3	251	-
5	Search 1 AND Search 2 AND Search 3	0	-	382	-
6	Search 1 INCLUDE Search 2	26	9	331	-
7	Search 1 INCLUDE Search 2 INCLUDE Search 3	0	-	26	2
8	Search 4 with 5-year criterion	-	-	237	-
9	Search 5 with 5-year criterion	-	-	344	-
10	Search 6 with 5-year criterion	-	-	290	-
11	Search 4 with 2-year criterion	-	-	195	8
12	Search 5 with 2-year criterion	-	-	274	8
13	Search 6 with 2-year criterion	-	-	233	4
14	Total	-	12	-	22
15	Final Total	-	-	-	34

*No – Number of the search; AR – Articles Retrieved; WOS R – Web of Science Results; SCO R – Scopus Results; Kset – Keywords set associated.

Table 2 presents the combinations of keywords derived from those listed in Table 1, varying their arrangement to assess the breadth of articles retrieved in the databases. Subsequently, the search scope was progressively restricted to obtain more accurate and manageable results for analysis. From these refined searches, only articles meeting the previously defined adherence criteria were selected for further examination.

The analysis of the countries associated with the 32 selected articles is presented in Figure 2. Figure 3 subsequently examines the topic on a broader scale.

Figure 2 shows that, among the 32 selected articles, Brazil had the highest number of publications (8), followed by Colombia (5), China (4), and Belgium, the United States, India, and Italy, with 3 articles each. It is worth noting that the total number of occurrences in the chart exceeds 32 because some articles include authors affiliated with institutions in multiple countries. This distribution highlights the strong presence of research in major cocoa producing countries, such as Brazil and Colombia, while also indicating significant contributions from countries with established research infrastructures, such as Belgium and the United States. These findings suggest the presence of both regional expertise and international collaboration in the field.

To determine whether this pattern resulted from search bias or the scope of the search strategy, an additional analysis was conducted using Search 5 and the Scopus analytical tools to identify the countries associated with the articles. The results presented in Figure 3 show that the ranking changed substantially, with India emerging as the leading contributor, followed by Nigeria, the United States, Malaysia, China, Brazil, Colombia,

Figure 2. Quantitative analysis of articles based on the location of the publication.

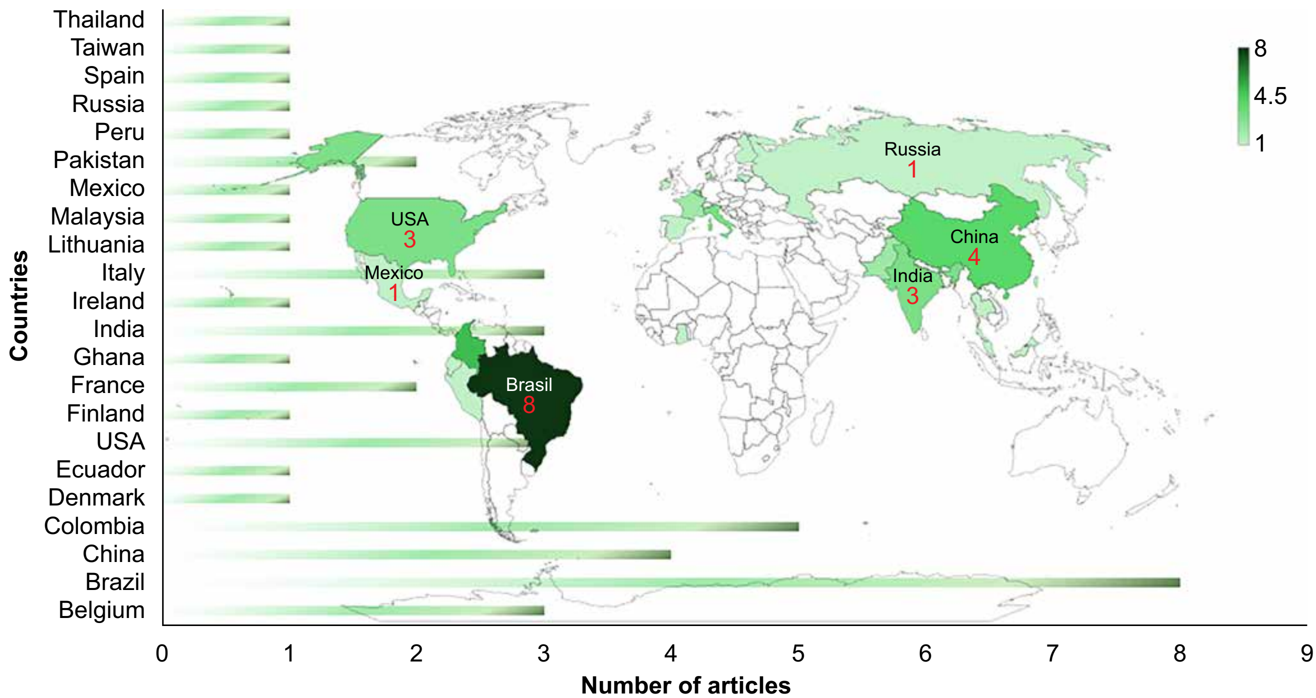
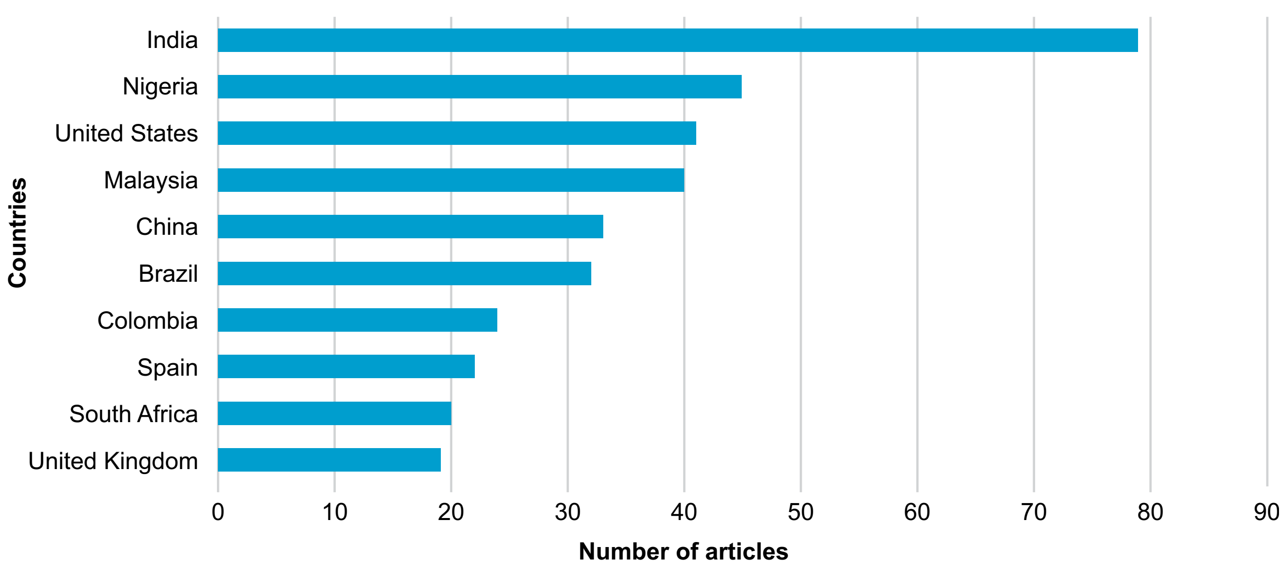


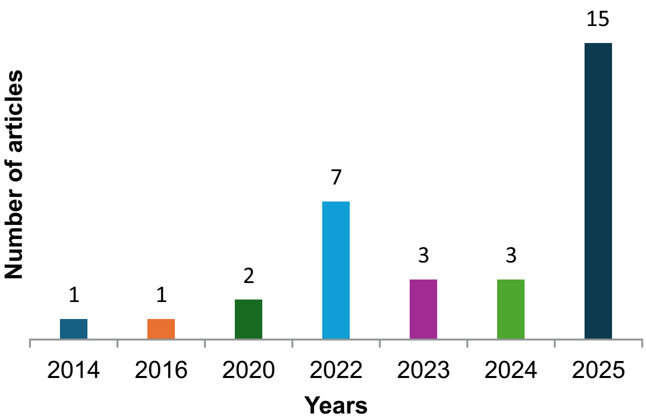
Figure 3. Quantitative analysis of articles (Scopus Analysis-Search 5) main countries of the papers.



Spain, South Africa, and the United Kingdom. This shift indicates that broader search criteria capture a more diverse set of contributors, reflecting not only cocoa-producing countries but also nations with active research programs in bioenergy, waste valorization, and biorefinery technologies. These findings suggest that the observed differences may be more closely related to the scope of the search strategy than to an inherent concentration of research in specific regions.

Subsequently, both approaches were used to assess annual publication output, as shown in Figures 4 and 5, with the aim of examining trends in interest in the topic over time. The results reveal fluctuations in publication numbers, with recent years showing a noticeable increase, suggesting

Figure 4. Quantitative analysis of articles based on year of publication.



that research on cocoa residue biorefineries is gaining momentum.

This upward trend may be linked to growing global attention to circular economy strategies, renewable energy sources, and the valorization of agricultural residues, suggesting that the field is transitioning from an emerging niche to a more established research area.

The Scopus data presented in Figure 5 include publications dated after 2025, likely because early access articles have been assigned to future issues. The leading journals within the set of 32 selected articles were analyzed, as shown in Figure 6, to identify the main publication venues in the field. The results reveal a concentration of publications in journals specializing in cocoa residue valorization and biorefinery technologies. This concentration indicates the growing relevance and thematic consolidation of the field and may contribute to further advances.

Using the Scopus analytical tools, the institutional affiliations associated with the articles were examined, as shown in Figure 7. This analysis provides insights into which universities, research centers, and organizations are most actively engaged in studies related to cocoa residue valorization and biorefineries.

Identifying these leading institutions is valuable for mapping potential collaborators, understanding regional research capacities, and recognizing centers of excellence in the field. Moreover, affiliation patterns can reveal the extent of international cooperation, with multi institutional and cross country partnerships often indicating more comprehensive and impactful research outputs.

The most prolific authors were also analyzed using the Scopus analytical tools, as shown in Figure 8. This examination highlights researchers with a consistent track record in studies on cocoa residue valorization and biorefineries. Recognizing these leading authors is important for mapping expertise, fostering potential collaborations, and understanding the intellectual structure of the research domain. Moreover, the recurrence of certain authors across multiple publications

Figure 5. Quantitative analysis of articles (Scopus Analysis-Search 5) based on year of publication.

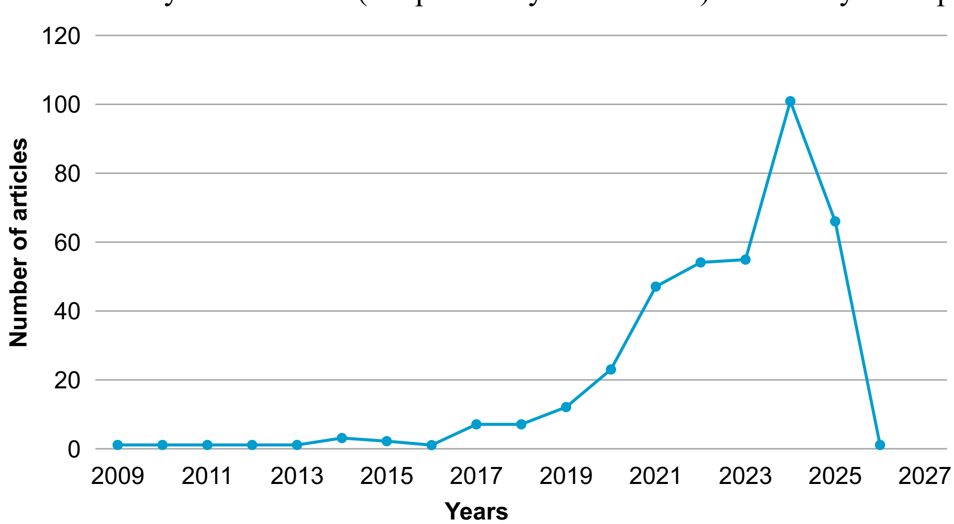


Figure 6. Quantitative analysis of articles based on journal publication.

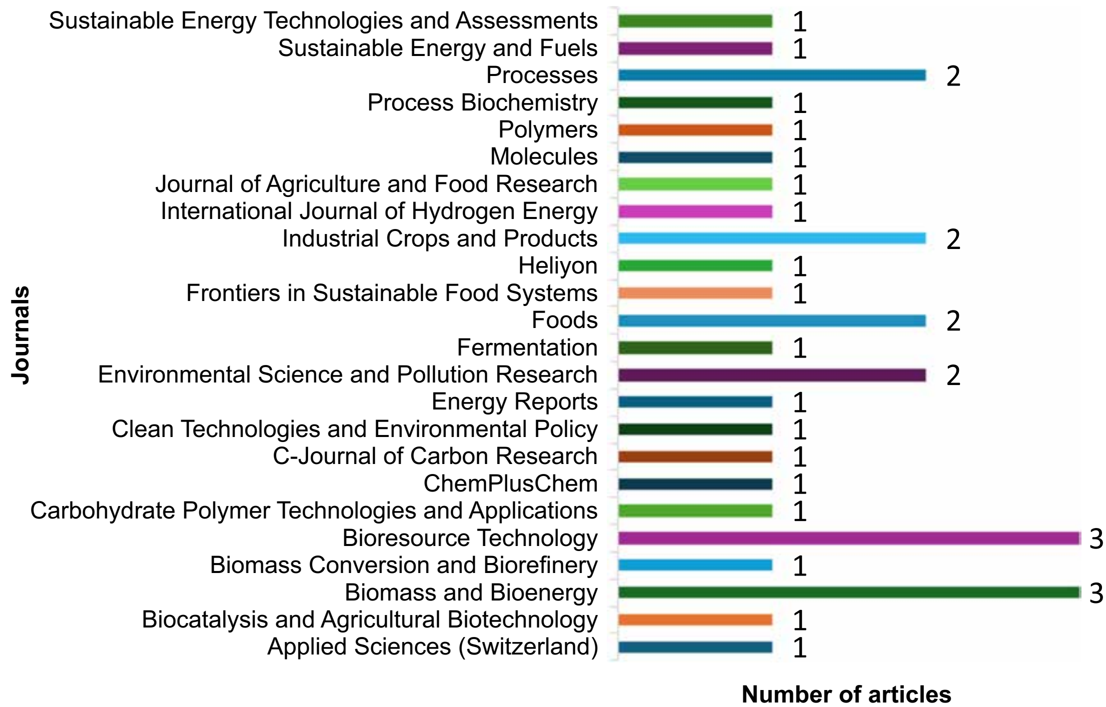
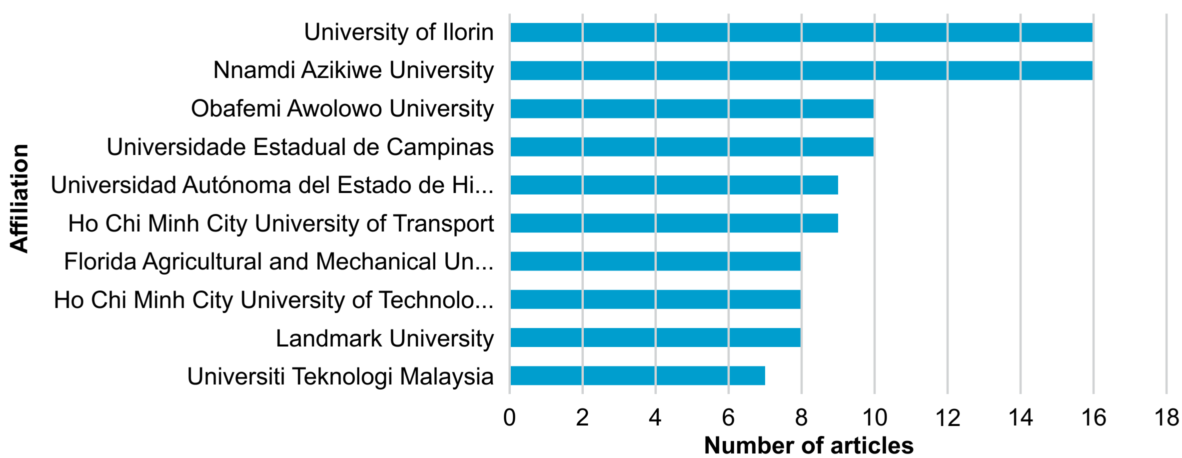


Figure 7. Quantitative analysis of articles (Scopus Analysis-Search 5) affiliation of the papers.



highlights their sustained research activity in the field and may reflect their contribution to the development of thematic trends and research directions. Subsequently, co authorship and keyword co occurrence analyses were performed using VOSviewer® for both the 32 selected articles and the results of Search 5, as presented in Figures 9, 10, and 11.

These network maps illustrate the main research collaborations and thematic areas, highlighting prominent authors, recurring topics, and emerging themes. They are useful for identifying research groups, tracking thematic shifts, and identifying opportunities for new collaborations.

The co authorship network analysis revealed a relatively fragmented research structure, with several small to medium sized clusters and limited interconnections among them. Among the most prominent and prolific authors in the network were Ighalo, I.O., and Adeniyi, A.G., whose

Figure 8. Quantitative analysis of articles (Scopus Analysis-Search 5) main authors of the papers.

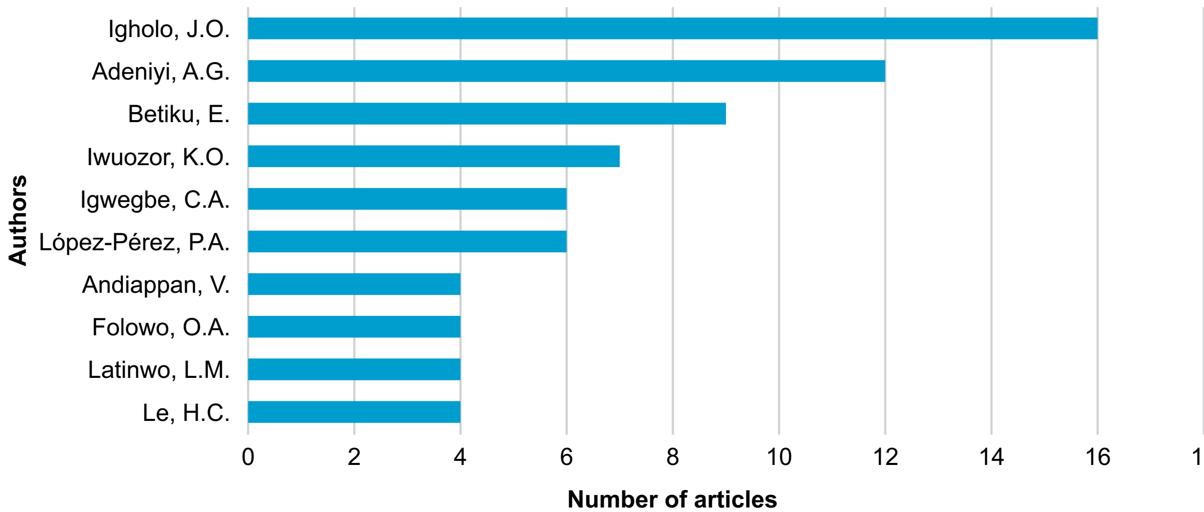
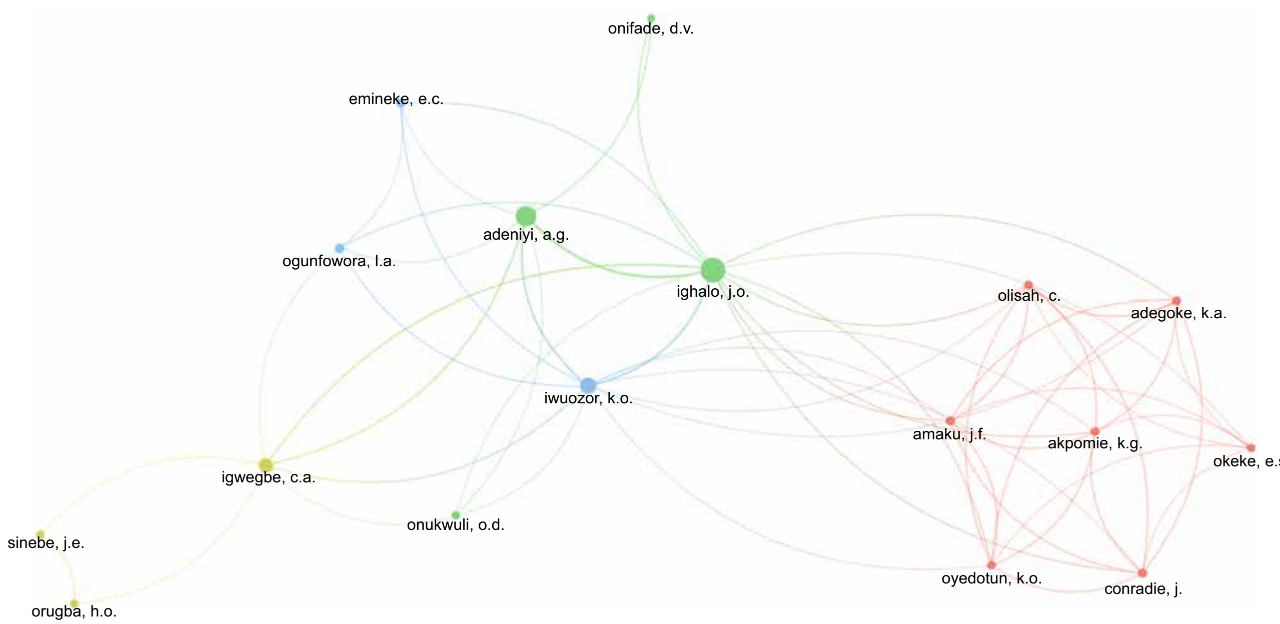


Figure 9. Co-authorship analysis in network format generated by VOSviewer (Search 5).

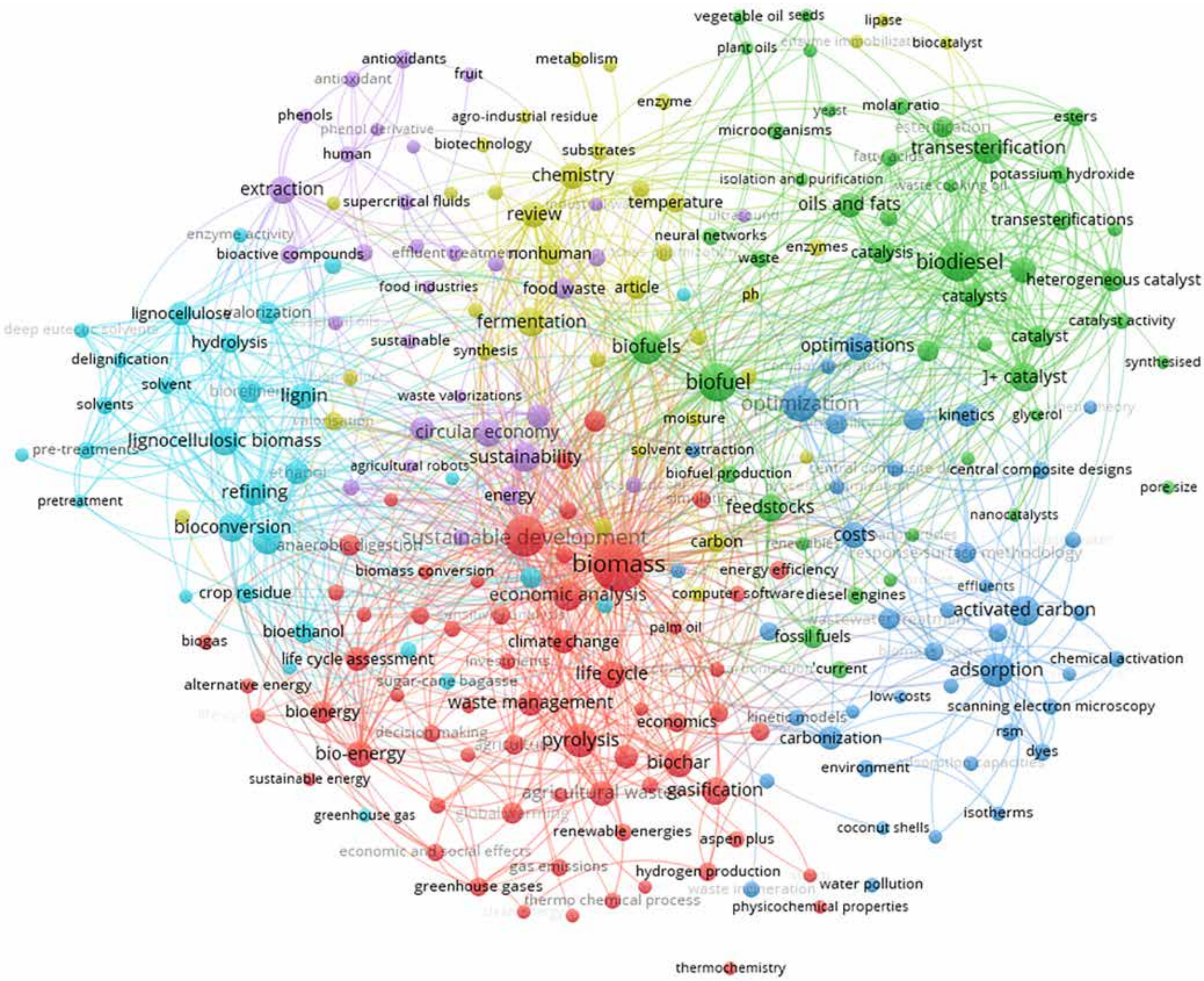


publications frequently address thematic areas related to biomass utilization, waste valorization, and sustainable process development. Their prominence within the network indicates a high level of research activity, with collaborations spanning multiple institutions and, in some cases, national borders.

In Figure 10, the most prominent keywords were biomass and sustainable development, which appeared in the same cluster. Overall, six distinct clusters were identified, focusing on biodiesel, lignocellulosic biomass, adsorption, fermentation, sustainability, and the circular economy. This thematic segmentation illustrates the breadth of research topics represented in the dataset, ranging from technological conversion processes to broader sustainability frameworks.

The presence of clusters dedicated to both specific processing routes, such as biodiesel production and adsorption techniques, and overarching concepts, such as sustainability and the circular economy,

Figure 10. Keyword co ocurrence analysis in clusters through network visualization in VOSviewer® (Search 5).

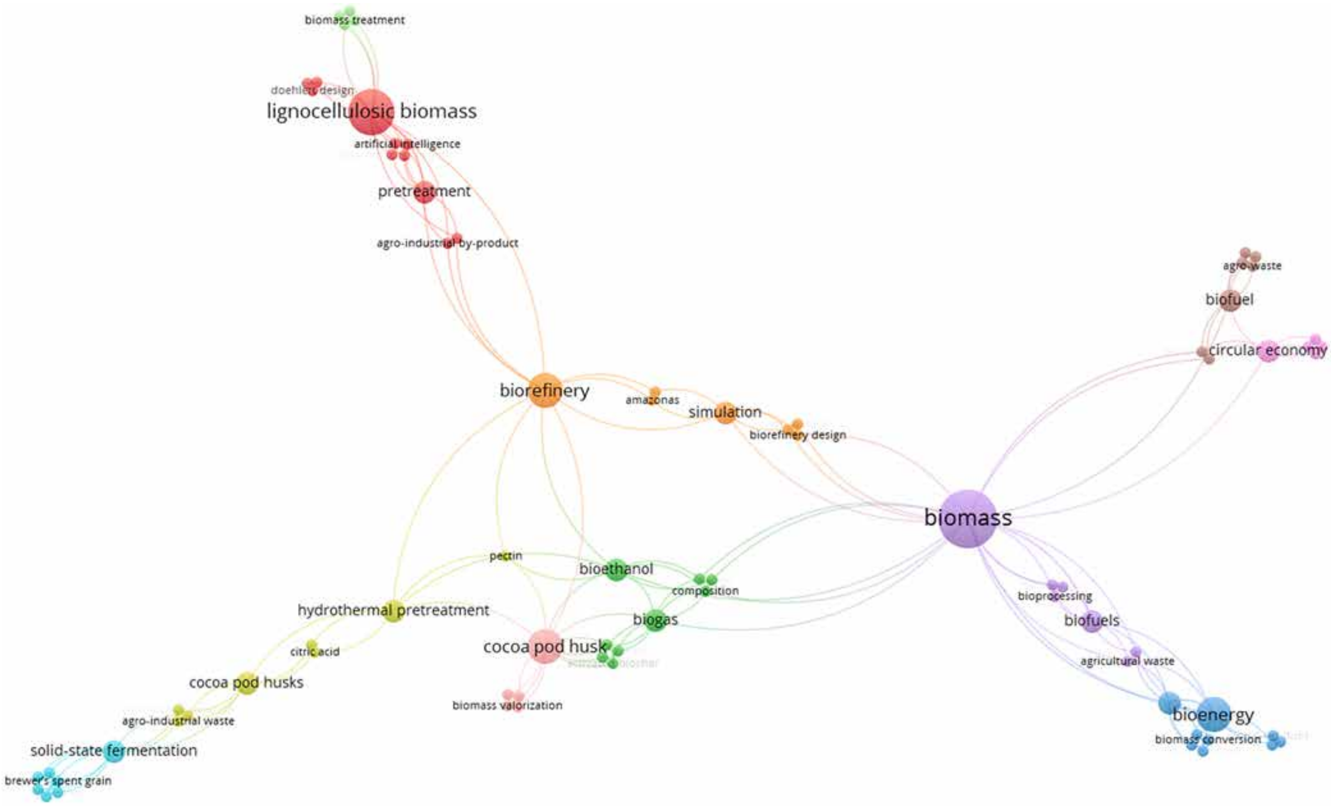


suggests that the field integrates applied technical studies with broader strategic perspectives. Such diversity reflects the multidisciplinary nature of biorefinery research and indicates opportunities for cross-cluster collaboration to strengthen links between technological innovation and sustainable development goals.

In Figure 11, biomass emerged as the most prominent keyword, forming the core of one of the clusters. In total, 11 clusters were identified. The main thematic areas included biodiesel, bioenergy, the association between bioethanol and cocoa pod husk, the relationship between hydrotreatment and solid state fermentation, lignocellulosic biomass and its association with biorefineries and biomass utilization, biomass treatment, and the circular economy. This diversity of clusters indicates a wide thematic range, spanning from specific conversion technologies (e.g., hydrotreatment, fermentation, biodiesel production) to broader sustainability-oriented frameworks such as the circular economy.

The proximity of cocoa pod husk to bioethanol in the network highlights a recurring research direction exploring its potential as a feedstock

Figure 11. Keyword co ocurrence analysis in clusters through network visualization in VOSviewer.®



for renewable fuel production. Meanwhile, the prominence of lignocellulosic biomass and biorefinery related terms indicates that studies on cocoa residues are aligned with established biomass valorization strategies, suggesting opportunities to integrate cocoa waste research into broader biorefinery and circular economy frameworks. Finally, a categorical analysis, presented in Figures 12 and 13, classified the studies as informational research, computational simulation, experimental study, data analysis, or mathematical modeling, clarifying their thematic focus, methodological diversity, and applicability.

This classification provides a clearer understanding of the methodological diversity of the selected studies and helps identify their thematic focus, technical depth, and potential applicability. TThe results indicate a predominance of informational studies, with fewer studies involving computational simulations or experimental approaches. This distribution suggests that, although the topic is conceptually established, significant opportunities remain for applied and integrative research that could bridge the gap between theoretical propositions and practical implementation.

Among the 32 selected articles, none employed process simulation to address the central research question. However, the studies by Valladares Diestra and colleagues [4] and Santos and colleagues [5] address cocoa residue biorefineries and may serve as key references by providing relevant data and methodological approaches for future research and the development of integrated, scalable, and economically viable processes.

The direct answer to the article's central question is a qualified yes: studies on cocoa residue biorefineries do exist in the scientific literature; however, no studies employing process simulation were identified.

Figure 12. Distribution of the selected articles by study category.

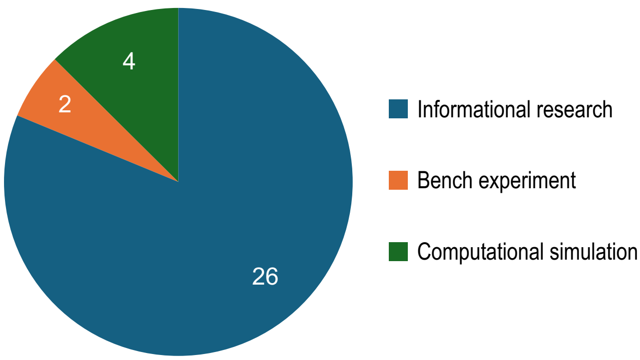
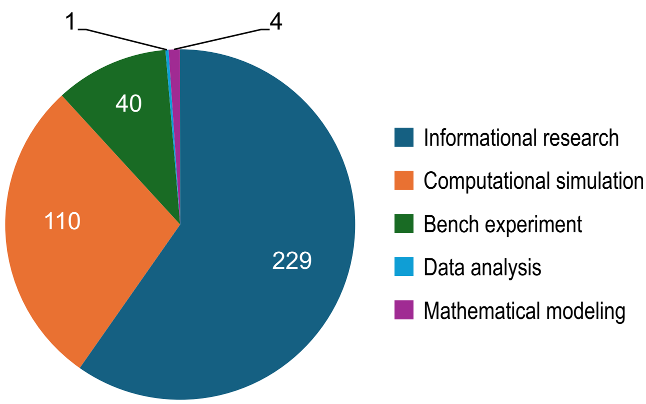


Figure 13. Distribution of articles by study category according to Scopus Search 5.



The field remains at an emerging stage, with considerable scope for further research, particularly regarding the integration of simulation based approaches with experimental and analytical studies. Expanding research on process integration, large scale feasibility, and sustainability assessment will be essential to advancing this field.

Conclusion

The analysis confirmed that studies on cocoa residue biorefineries exist, although no research employing process simulation was identified.

The field remains at an early stage, with research concentrated in regional initiatives. Bioenergy and bioactive compounds are the most explored themes, while research on integrated process design, large scale feasibility, and economic viability remains limited.

These findings highlight the need for applied interdisciplinary approaches and stronger collaboration. Future research should prioritize process simulation alongside experimental studies and techno economic assessments to support the development of sustainable cocoa based biorefineries.

Acknowledgement

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Exploring *Prosopis juliflora* as a Sustainable Biomass Source for Bioethanol: A Review of Processing Methods and Production Potential

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As the 20th century progressed, the accelerated growth of industry and the consistent increase in population size in major urban areas contributed to an escalating release of greenhouse gases, including carbon dioxide (CO_2). Fuels derived from renewable materials, such as plant biomass, offer an alternative to traditional fuels, providing a more environmentally friendly energy source. A highly relevant alternative would be to align the development of sustainable technologies with the bioprocessing of biomass waste from non-food sources. The tree *Prosopis juliflora* (*P. juliflora*) is a promising candidate due to its accessibility and energetic properties. The success of *P. juliflora* biofuel hinges on pretreatment techniques that maximize enzymatic accessibility to cellulose. This study systematically reviews the extant research on *P. juliflora* as bioethanol feedstock, with a focus on identifying which plant parts are used, the treatments applied to these parts, and the methods employed for biomass breakdown. The research methodology entailed a bibliometric analysis, which was conducted using the Web of Science database between July 25, 2025, and August 5, 2025. The Vosviewer® software was utilized for the analysis of keyword co-occurrence and author co-citation. The search yielded 29 publications and 32 keywords, with a minimum of three occurrences in the analyzed articles. Of these, 20 publications met the study's scope. The findings of the study demonstrate that chemical pretreatment provides the optimal balance between delignification and cellulose preservation. Acid degradation is still preferred over enzymatic hydrolysis, as it is the approach used in most of the studies that were analyzed. While there are studies that have applied *P. juliflora* in the production of bioethanol using these strategies, the development of more sustainable research and methodologies is still necessary to obtain biofuel in an effective and ecological way.
Keywords: Bioethanol. Delignification. Enzymes. Fermentation. *Prosopis juliflora*.
Abbreviations: IEA, International Energy Agency. EPE, Brazilian Energy Research Corporation. CO_2, carbon dioxide. Nox, nitrogen oxides. WoS, Web of Science.

The increase in population and industrialization has resulted in higher consumption of non-renewable fossil fuels and accelerated global warming and climate change [1-3]. Globally, CO_2 is the most prevalent greenhouse gas, mainly from energy production. In 2023, energy-related CO_2 emissions rose by 1.1% to approximately 37.4 Gt, with over 40% from electricity and heat, followed by transport and manufacturing [4-6]. NOx emissions from vehicles, power plants and industry are a significant contributor to air pollution, with road transport accounting for nearly half of total emissions. Agriculture, via synthetic fertilisers, is a significant source of N_2O, another potent greenhouse gas [7-8]. Ethanol's advantages make it an increasingly viable alternative or complementary transport fuel, boosting global research on renewable biofuels [9]. In this context, *Prosopis juliflora* (commonly known as algaroba or mesquite) is a promising biomass resource to ethanol producing [10].

P. juliflora trees are native to North and South America [11-13]. The fruits of *P. juliflora* (pods) are historically known for their palatability due to their high sucrose content, similar to corn and barley [11]. *P. juliflora* lignocellulosic biomass is notable for its capacity to release high levels of sugars as a result of cellulose and hemicellulose. These polymers consist of residual units of glucose and xylose [14]. These sugars can be fermented to produce ethanol. However, the presence of lignin in lignocellulosic biomass makes it need an effective

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pretreatment process to facilitate cellulose and hemicellulose conversion into fermentable sugars for bioethanol production [14]. The aim of the present study is to provide a comprehensive review of existing research on the use of *Prosopis juliflora* as a feedstock for bioethanol production.

Materials and Methods

The research methodology was bibliometric analysis. The study had three steps: (1) data collection, (2) data visualization, and (3) data analysis.

Data Source and Collection

The search for keywords representative of the topic under study was carried out using the Web of Science database. Data collection in the databases was carried out between July 25, 2025, and August 5, 2025. The keywords were refined based on relevance and coverage to closely align with the research objectives and the gaps in this study.

The keywords were divided into three main groups: (a) Feedstock: ("*prosopis juliflora*" OR "algarob*" OR "algarrob*" OR "mesquite"); (b) Process: ("pretreatment" OR "delignification" OR "biomass pretreatment" OR "biomass delignification" OR "pretreatment of lignocellulose" OR "ethanol production" OR "fermentative microorganisms" OR "fermentation conditions" OR "ethanol fermentation" OR "distillation process" OR "fermentation optimization"); and (c) Product: ("biofuel" OR "renewable fuels" OR "bioethanol" OR "ethanol" OR "second-generation ethanol" OR "cellulosic ethanol" OR "lignocellulosic ethanol"). Quotation marks ("") were used to delimit the search term. The asterisk (*) was used to find words written with the same prefix and different endings, such as "algarob*" for "algaroba" and "algarobo", for example.

The keywords were indexed in the database following three distinct phases: (I) search for keywords groups; (II) search for keywords groups combinations; (III) search for keywords groups combinations using inclusion criteria. using the Boolean operator "OR", separating the combinations of terms within the same group to combine equivalent terms, and the operator "AND", to combine the different groups to form the research descriptors.

The results were filtered by selecting only English-language articles published in the last two decades (from 2005 to 2025) and impact factor above 0.5 (2023/2024). The search parameters were "All fields" to result in more publications.

Data Visualization and Analysis

Vosviewer® software was used for the analysis of keyword co-occurrence and author co-citation. The co-occurrence of keywords was used to map the intensity of the association between terms used in the keywords of the publications extracted, filtering the keywords for a minimum of 3 occurrences. Co-citation was used to measure the degree of collaboration between authors, countries and institutions, and the citation of a given author. These associations were represented by cluster networks generated by Vosviewer software.

The data obtained were analyzed evaluating the number of publications by author, country, year, publisher, and research area.

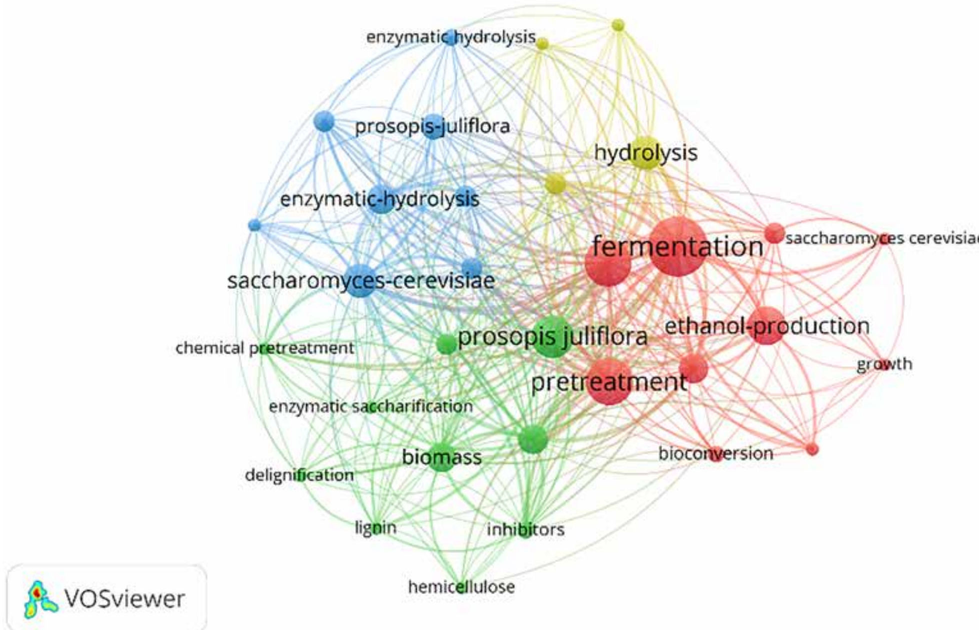
Results and Discussion

Bibliometric Analysis

The search on Web of science resulted in 3.084 publications *P. juliflora* using specific descriptors for feedstock. When searching for articles in English using descriptors related to feedstock, process and product, the database provided 29 publications.

The visualization of the research data in Vosviewer showed 32 keywords with a minimum of 3 occurrences in the analyzed articles, forming the network shown in Figure 1. The following keywords were of particular significance:

Figure 1. Representation of the co-occurrence of keywords on *P. juliflora* and bioethanol production.



"fermentation", exhibiting 14 occurrences; "bioethanol" and "pretreatment" with 11 occurrences; and "*prosopis juliflora*" with 10 occurrences each.

55% of the 29 studies analyzed in this research are in the Biotechnology Applied Microbiology area and 37% published by Elsevier between 2007 and 2022. During this period, there was a fluctuation from 0 to 4 publications/year, with a maximum of publications in 2016.

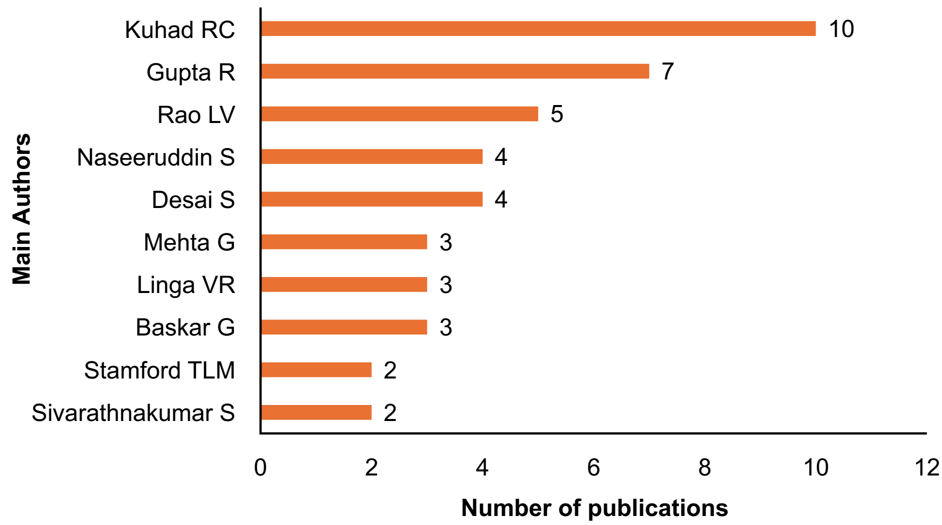
In the co-authorship analysis (Figure 2), of the 69 authors, two stood out with the highest number of publications: Ramesh C. Kuhad, with 10 publications, of which 7 have Rishi Gupta from the University of Delhi (India) as the main author. These authors had 547 and 455 citations, respectively.

79% of the studies published in this period originate from research groups linked to educational institutions in India that has intensified research into the use of new biomass for bioethanol production due to the implementation of the Ethanol Blended with Petrol Programme, which has the target of 20% blending of ethanol with petrol by 2025 to reduce the price of fuel and CO_2 emissions in the country [1]. The educational institutions that had more published on the topic were the University of Delhi and Osmania University, both in India, with 10 and 9 publications, respectively. Six Brazilian institutions appeared in three of the articles shown in the research. Researchers from the Federal University of Paraíba, Federal University of Pernambuco and Federal Rural University of Pernambuco collaborated on two studies that examined the use of *P. juliflora* pods as biomass for the growth of *Saccharomyces cerevisiae* and *Zymomonas mobilis* and producing ethanol. The Federal Institute of Bahia, the Federal University of Bahia and the Federal University of Reconcavo of Bahia have produced paper the use of *P. juliflora* wood for charcoal production.

Prosopis juliflora Bioprocessing to Produce Biofuel Review Analysis

Following a thorough review of the 29 articles extracted from Web of Science (WoS), 9 were excluded at this stage of the analysis. These were either on other types of biomass (e.g. banana, coconut, cotton, etc.) or were published in journals with an impact factor lower than 0.5 in 2023/2024.

Figure 2. Representation of number of publications by author on *P. juliflora* and bioethanol production.



Among the studies analyzed, the plant part most used was wood from the woody stem, used in 80% of studies on *P. juliflora* pretreatment. The wood sample is an excellent choice when one wants to study the efficiency of pretreatment. The wood from the stem will be more resistant to hydrolysis due to its high lignin content. During the pretreatment process, the lignin and hemicellulose contents are reduced, and the lignocellulosic materials are ready for cellulose digestion into fermentable sugars. In addition, the use of wood is chosen as a measure to eradicate *P. juliflora* in countries where it is considered a weed, such as India and Brazil [11,15]. Analyzing the 20 articles that were in accordance with the study criteria, 15 were about *P. juliflora* biomass pretreatment. 86% of studies on pretreatment of *P. juliflora* used chemical pretreatments with acid, alkaline solutions, and oxidizing or reducing agents. The remaining two studies used biological pretreatment using white rot fungus. The main chemical pretreatments described in the literature use sulfuric acid (acid pretreatment) and sodium hydroxide (alkaline pretreatment), isolated or combined. The highest delignification rate was obtained by Gupta and colleagues [16] carried out pretreatment in three steps: impregnating *P. juliflora* wood with sulfuric acid, followed by reduction with sodium sulfite and oxidation with sodium chlorite, obtaining 93% lignin removal. Regarding the biomass saccharification process, seven studies performed enzymatic degradation using commercial cellulase enzymes from Trichoderma reesei supplemented with exogenous β-glucosidases from *Aspergillus niger*. The other authors performed acid hydrolysis using sulfuric acid or nitric acid.

Twelve studies analyzed biofuel production using *P. juliflora* biomass as a substrate. Ten of these focused on bioethanol, one on biomethane and one on charcoal production. This fact shows that the use of *P. juliflora* in the bioenergy area is still minimal compared to its potential.

Conclusion

The *P. juliflora* tree has been the aim of study for decades due to its wide applicability. However, studies on the *P. juliflora* biomass pretreatment and its use in biofuel production are still scarce. Among 3,084 articles about *P. juliflora*, only 1.2% are about biomass pretreatment, and less than 1% are about the use of *P. juliflora* biomass to produce biofuels. Among the *P. juliflora* biomass pretreatments described in the literature analyzed, chemical pretreatment was the most used and with the highest yield, especially when performed at high temperatures.

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Potential of *Agave sisalana* in the Brazilian Semi-Arid Region for Ethanol and Biogas Production

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This study aims to conduct a bibliographic assessment of the potential of agave as a raw material for biofuel production in the Brazilian semi-arid region, considering agronomic, technological, and environmental aspects. Agave, a plant native to arid and semi-arid regions, stands out for its high biomass productivity and ability to adapt to conditions of low water availability. These characteristics make it a promising alternative for the sustainable production of biofuels, especially in areas less suitable for conventional agriculture. Unlike traditional crops such as sugarcane, agave cultivation does not compete directly with food production, which contributes to food security. Studies show that agave species can achieve ethanol yields of between 7,400 and 10,000 liters per hectare, which is competitive with or higher than the yields obtained from sugarcane in dry regions. In addition to ethanol, the bagasse and residual juice from the leaves can be used to generate biogas and biomethane, expanding energy utilization routes and assisting in the management of agro-industrial waste. Thus, agave has strategic potential to strengthen the renewable energy matrix, generate socioeconomic and environmental benefits, and contribute to climate change mitigation goals.
Keywords: Biofuels. Sustainability. Efficiency. Energy.

Recent studies have shown that Agave species have a high potential for conversion into biofuels, reaching ethanol productivities comparable to or even higher than sugarcane in semiarid regions, in addition to significant methane yields from leaf juice [1]. Strategic initiatives, such as the Brazilian Agave Development Program (BRAVE), have fostered research and the development of technologies aimed at harnessing agave as a renewable energy source, reinforcing its importance in the national energy matrix [2].

The growing demand for energy and concern about climate change have led to a search for renewable and sustainable energy sources. In this regard, biofuels present themselves as an alternative to fossil fuels, since they offer the chance to reduce greenhouse gas emissions, in addition to promoting rural development [3]. Brazil, with its large area and diversity of biomes, has enormous potential to produce biofuels from various raw materials. Sugarcane and corn have traditionally been the main sources for producing ethanol, while agro-industrial waste is used to produce biogas. Corn produces about 2,500 liters of ethanol and up to 18,540 m³ of biogas per hectare, generating between 6 and 12 tons of crop residues per hectare, such as stalks, leaves, and cobs, which can be used for energy generation. Sugarcane, on the other hand, has a productivity of around 7,000 liters of ethanol per hectare, generating approximately 280 kg of bagasse and straw for every 1,000 kg of processed cane. Vinasse, a liquid waste produced on a large scale in Brazil (around 360 billion liters/year), is used in the production of biogas and biomethane, where it is used to replace natural gas. In addition, the dispute over land that can be used for cultivation and over more water resources for food production has sparked debates about the sustainability of these crops [4]. In this case, the search for new

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raw materials that do not compete with food and are ready for difficult climate conditions becomes very important. Agave Sisalana is a succulent plant that comes from dry and semi-arid regions, and has shown great potential for producing biofuels. Its particular resistance to drought, high mass, and ability to store fermentable sugar make it a strategic choice for places such as the Brazilian semi-arid region, where water scarcity is a major problem for normal agriculture [5]. In addition, we have observed that agave sisalana shows promising potential for biofuel production, especially in the semi-arid regions of Brazil. Estimates indicate that agave can produce about 7,400–10,000 liters of ethanol per hectare per year. These yields are competitive with sugarcane, especially in regions with limited water resources.

Agave, a plant adapted to arid and semi-arid regions, has high biomass productivity, low water consumption, and does not compete directly with food crops, characteristics that make it a strategic alternative for energy transition. This study aims to conduct a bibliographic evaluation of the potential of agave as a raw material for the production of biofuels in the Brazilian semi-arid region, considering agronomic, technological, and environmental aspects.

Agave as a Product for Biofuels

Agave spp. is a perennial plant highly adapted to poor soils and low rainfall conditions, typical characteristics of arid and semi-arid regions. The high water efficiency of agave is attributed to crassulacean acid metabolism (CAM), an adaptive biochemical mechanism that optimizes water use in arid and semi-arid environments. During the night, when the temperature is lower and the relative humidity is higher, the stomata remain open to allow carbon dioxide (CO_2) to enter, minimizing water loss through evapotranspiration. CO_2 is initially fixed by the enzyme phosphoenolpyruvate carboxylase (PEPC) in the cytoplasm, forming oxaloacetate (OAA), which is rapidly converted to malate by a malate dehydrogenase. Malate is then stored in cell vacuoles in the form of organic acids. During the day, with the stomata closed to prevent water loss, malate is transported to the chloroplast, where it is decarboxylated to release concentrated CO_2, which is fixed again by Rubisco in the Calvin cycle, allowing the synthesis of carbohydrates. This temporary carbon fixation system maximizes CO_2 assimilation and drastically reduces transpiration, giving agave high water use efficiency, which is essential for its survival and productivity under water stress conditions. In addition to its resilience in adverse environments, agave accumulates large amounts of carbohydrates in the form of fructans, predominantly inulin, stored in its stem and leaves. Biochemically, inulin is a polysaccharide formed by chains of fructose units linked by β (2→1) bonds, with a terminal glucose molecule, which serves as an energy reserve. These polymers can be hydrolyzed by specific enzymes called inulinases, which break the glycosidic bonds, releasing simple sugars such as fructose. These sugars are then fermented by microorganisms, mainly yeasts of the genus Saccharomyces, which metabolize fructose via glycolysis, converting it into ethanol and carbon dioxide, a process known as alcoholic fermentation. After the extraction of fermentable sugars or fibers, the residual bagasse remains rich in lignocellulosic material and other organic compounds. This residue is a viable substrate for biogas production through anaerobic digestion, a microbial process in which complex polysaccharides are initially degraded into simple sugars, fermented into organic acids, and finally converted into methane and carbon dioxide by methanogenic microorganisms. In this way, the energy use of the crop is expanded, promoting the integration of sustainable bioenergy routes. [6].

<u>Potential for Ethanol</u>

The production of ethanol from agave has been increasingly discussed due to its high yield potential. Comparative studies point to agave as a superior competitor to sugarcane by around 24% in terms of liters of ethanol per hectare under specific conditions, mainly where there are water constraints [7]. Ethanol can be produced in the first generation from directly fermentable sugars in the biomass, and in the second generation from the cellulose and hemicellulose present in the bagasse [8]. Agave's main fermentable sugars are fructose and glucose, which come from the breakdown of fructans present in the plant. These simple sugars are used in the production of first-generation ethanol. Solid residues, such as bagasse, which contain cellulose and hemicellulose, can be converted into sugars for the production of second-generation ethanol. Thus, agave can provide raw material for ethanol production from both sugars and its residual biomass.

On the other hand, optimizing the processes of fructan hydrolysis and fermentation is essential to increase the efficiency of agave ethanol production. New biotechnological strategies, such as the use of genetically engineered yeast strains, are also being researched to improve sugar conversion and inhibitor tolerance [9].

Potential for Biogas and Biomethane

A widely available by-product of the sisal fiber and beverage industries, such as tequila and mezcal, agave bagasse represents a valuable source of biogas. There are many ways to deal with the anaerobic digestion of lignocellulosic biomass, which is why biomass, even when complex, can be efficiently degraded after pretreatment actions [10]. More recent research is examining the juice from the plant's leaves, which is routinely discarded, as a useful substrate for biogas production when supplemented with an enhancer and other nutrients [11]. The production of biogas from agave not only provides an efficient source of renewable energy, but also contributes to the management of agro-industrial waste. Furthermore, the use of biogas will reduce emissions of methane, a potent greenhouse gas that contributes to climate change. This biogas can be purified and transformed into biomethane, a direct alternative to natural gas, which can even be used to generate electricity, heating, and vehicle fuel [12].

Materials and Methods

This study consists of a bibliographic survey aimed at assessing the potential of Agave spp. as a raw material for the production of biofuels in the Brazilian semi-arid region in comparison with corn and sugarcane. The research was conducted through the analysis of scientific articles, dissertations, theses, and technical documents published in recognized databases, such as Scopus, Web of Science, Scielo, and Google Scholar. The selection criteria included publications between 2020 and 2022 in Portuguese, English, and Spanish, focusing on the following topics: agronomic characteristics of agave, CAM metabolism, physical-chemical and energetic composition, pretreatment technologies, alcoholic fermentation, anaerobic digestion, and crop viability in semi-arid regions.

Results

This study is expected to contribute significantly to the consolidation of the pilot project currently under development, aimed at the sustainable production of biofuels from native and cultivated species of Agave spp. in the Brazilian semi-arid region. The survey should provide comprehensive data on physical-chemical and energy attributes, with the aim of validating its potential as a strategic raw material for the production of ethanol, biogas, and biomethane. Based on this information, it will be possible to propose technological improvements aimed at maximizing yields, both in alcoholic fermentation and anaerobic digestion, boosting the efficiency and sustainability of bioenergy processes [16].

Chemical Composition of Agave

The chemical composition of agave, although it may vary slightly between species and parts of the plant such as leaves, stem, and bagasse, has consistent characteristics that make it promising for bioenergy applications. As shown in Table 1, fructans, mainly in the form of inulin, represent 10 to 25% of the dry matter of agave. These fructose polymers are the main source of fermentable sugars, such as fructose and glucose, which can be easily converted into biofuels, standing out in the glycolytic process due to their rapid energy availability.

The lignocellulosic fraction of agave, composed of cellulose, hemicellulose, and lignin, constitutes most of the biomass, especially in the residual bagasse after the extraction of soluble sugars. Cellulose varies between 30 and 45%, while hemicellulose represents 15 to 25% of the composition, together totaling a large amount of structural polymers that can be converted into fermentable sugars after appropriate pretreatment. Lignin, present in 10 to 20%, provides structural strength and hinders biodegradation, making it a critical factor to consider in processing for second-generation biofuels. In addition, the presence of free sugars (2 to 5%) and ash (3 to 8%) completes the typical chemical profile of agave, influencing the biochemical conversion stages and the quality of the residue for different energy routes. Thus, agave bagasse, with its rich composition of lignocellulosic polymers and fructans, is recognized as a valuable raw material for the sustainable production of advanced biofuels, combining energy efficiency with full utilization of biomass [17].

Although the chemical composition of agave may vary between species and parts of the plant, such as leaves, stem, and bagasse, it will have consistent characteristics, making it promising for bioenergy applications. As shown in Table 1, the typical composition of Agave spp. (dry basis) for bioenergy purposes is observed, highlighting the fractions of fructans, cellulose, hemicellulose, lignin, and other components relevant to biofuel conversion processes. These data reinforce the crop's potential for both first-generation ethanol, derived from fermentable sugars, and second-generation ethanol, using biomass containing lignocellulose.

Table 1. Typical composition of Agave (dry basis) for bioenergy purposes.

Component	Concentration Range (%)
Fructans (Inulin)	10 - 25
Cellulose	30 - 45
Hemicellulose	15 - 25
Lignin	10 - 20
Free Sugars	2 - 5
Ash	3 - 8

Source: Based on Mendes [17].

Ethanol Yield: Agave *vs*. Sugarcane

In general, agave has an ethanol yield per hectare that is competitive with sugarcane, and according to some authors, it is even higher in semi-arid regions [18]. To highlight this comparison, Table 2 presents estimates of biomass yield and ethanol production per hectare for the two crops, thus emphasizing the advantage of agave in terms of productivity and adaptability to water stress conditions. This visualization allows us to better understand the relevance of this crop for diversifying the energy matrix, especially in areas with limited water resources. Sugarcane yield in Brazil averages approximately 79 tons/hectare, with ethanol production varying. Agave, on the other hand, can achieve promising yields, especially considering its adaptability to water stress conditions [19].

A comparative analysis between sugarcane and agave reveals important differences in terms of

Table 2. Comparison of biomass and ethanol yield per hectare (estimates)

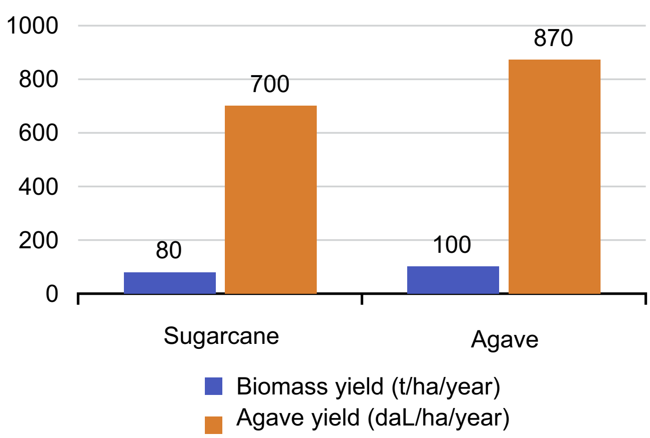
Raw Material	Biomass Yield (tons/ha/year)	Ethanol Yield (liters/ha/year)
Sugarcane	70 - 90	6,000 - 8,000
Agave	80 - 120	7,400 - 10,000

Source: Based on Oliveira and Ministério da Saúde [18,19].

biomass yield and potential for ethanol production. As shown in the table, agave has a higher biomass yield, ranging from 80 to 120 tons per hectare per year, while sugarcane produces between 70 and 90 tons in the same period. This higher biomass yield of agave can be attributed to its adaptation to adverse environmental conditions, such as poor soils and semi-arid climate, where its water efficiency and crassulacean acid metabolism (CAM) contribute to maximizing growth even under restrictive conditions (Table 2).

Figure 1 shows a comparison of the annual biomass and ethanol yields between sugarcane and agave, highlighting significant differences between these two important crops for bioenergy production. Agave has a slightly higher biomass yield, at around 100 tons per hectare per year, compared to 80 tons for sugarcane.

Figure 1. Comparison of biomass and ethanol yield: Sugarcane *vs*. Agave



In terms of ethanol yield, agave also has greater potential, producing approximately 870 decaliters per hectare per year, compared to 700 decaliters for sugarcane. This advantage can be attributed to the high concentration of fermentable sugars, mainly fructans such as inulin, in addition to the possibility of using lignocellulosic biomass for second-generation ethanol. Thus, agave stands out not only for its higher biomass productivity, but also for its versatility and efficiency in converting its components into biofuels. It is worth noting that agave yield can vary depending on the species, agricultural management, and pretreatment and fermentation technologies employed. Thus, agave emerges as a promising alternative for diversifying the energy matrix, especially in regions with water limitations where sugarcane is less adaptable.

Biogas Production from Agave

Agave bagasse and agave leaf juice are promising substrates for biogas production with the help of anaerobic digestion of agave bagasse. The biochemical methane potential (BMP) value of agave bagasse is variable. However, studies suggest that biodegradability and methane production can be adjusted for greater efficiency with the right pretreatments, such as steam and enzymatic hydrolysis, which are good examples [20].

Agave, a plant adapted to arid and semi-arid regions, has high biomass productivity, low water consumption, and does not compete directly with food crops, characteristics that make it a strategic alternative for energy transition. Recent studies highlight that residues and by-products, such as bagasse and leaf juice, have a high sugar content and can be used in anaerobic digestion for methane production, achieving yields of over 600 NmL CH_4/gVS with nutritional supplementation, in addition to significant potential for electrical and thermal energy generation [1]. Table 3 shows the Biochemical Methane Potential (BMP) of different fractions of agave, expressed in milliliters of CH_4 per gram of volatile solids (VS). It can be observed that agave bagasse has a BMP ranging from 150 to 250 mL CH_4/g VS, while agave leaf juice has higher values, ranging from 250 to 350 mL CH_4/g

Table 3. Methane production potential of agave waste.

Substrate	Biochemical Potential of Methane (BMP) ($mL\ CH4/g\ SV$)
Agave Bagasse	150 - 250
Agave Leaf Juice	250 - 350

VS. This difference is directly associated with the biochemical composition of each substrate: bagasse is predominantly lignocellulosic, containing high proportions of cellulose, hemicellulose, and lignin, whose biodegradability is limited due to the structural complexity and recalcitrance of lignin. In contrast, leaf juice is rich in soluble carbohydrates, mainly fructose and glucose, derived from the hydrolysis of fructans, which provides greater availability of readily fermentable substrates for methanogenesis.

The observed BMP can potentially be increased through the use of physical-chemical or biological pretreatments that increase the enzymatic accessibility of the lignocellulosic fraction, as well as through adjustments to the agave cultivation conditions that favor greater accumulation of soluble sugars. Thus, the analysis of these values provides insights to optimize the full use of agave in biogas production, integrating valorization routes for both the liquid and solid fractions of the plant.

Conclusion

Under current conditions, agave emerges as a strategic and sustainable agent for biofuel production in the Brazilian semi-arid region. Its resistance to harsh conditions, high biomass production capacity, and potential for ethanol and biogas production position it as a high-value crop for diversifying the energy matrix and promoting regional socioeconomic development. The proposal of this study, based on methodological rigor, aims to fill knowledge gaps and develop subsidies for the implementation of efficient and non-integrated conversion technologies. The valorization of agave as a raw material for biofuels is a crucial milestone on the path to the energy future.

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UAV-Driven Maritime Object Detection and Classification: Literature Review of AI Models, Data, and Performance

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This literature review explores the integration of UAVs and AI in maritime surveillance, analyzing 59 peer-reviewed studies from 2020–2025. It highlights trends in object detection and classification, common methodologies, model architecture (notably YOLO), and evaluation metrics like mAP. Detection targets include boats, ships, and swimmers, with varying research focus. The review identifies technological approaches, research gaps, and growing interest in UAV-based maritime monitoring.
Keywords: UAV. Maritime Environment. Object Detection. Model Architecture. Machine Learning.
Abbreviations: UAV, Unmanned Aerial Vehicle. mAP, mean Average Precision. CNN, Convolutional Neural Network. IoU, Intersection over Union. FPS, Frames Per Second. AI, Artificial Intelligence.

Marine environments present challenges for object detection, these environments are typically more adverse and unstable than those encountered in autonomous driving applications, due to factors such as fog, rain, wave interference, shoreline complexity, and the absence of structured features like lane lines, all of which significantly reduce visibility [1]. Traditional monitoring systems also face limitations related to spatial coverage, temporal constraints, and operational costs. They often face limitations related to spatial coverage, temporal constraints, and operational costs [2].

Unmanned Aerial Vehicles (UAVs) integrated with Artificial Intelligence (AI) have emerged as an alternative approach for maritime object detection and classification, these can operate in coastal areas, harbors, and open ocean locations to collect imagery for monitoring. Their efficient deployment is particularly valuable when large regions need to be rapidly surveyed [3].

This literature review analyzes UAV-based maritime surveillance with AI integration by surveying methodological approaches, comparing performance across detection targets (vessels and swimmers), examining architectural preferences and evaluation metrics, and identifying research gaps.

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Materials and Methods

The study is characterized as exploratory, using literature review as method and bibliometric analysis as procedure, assisting in trends identification in knowledge expansion in UAV maritime object detection, as well as research gaps, and in the identification of journals most used for research dissemination in this specific area.

The study design was divided into three main stages: planning, conduction, and systematization (Figure 1). From the objective, a protocol was developed with research questions, keywords, inclusion and exclusion criteria.

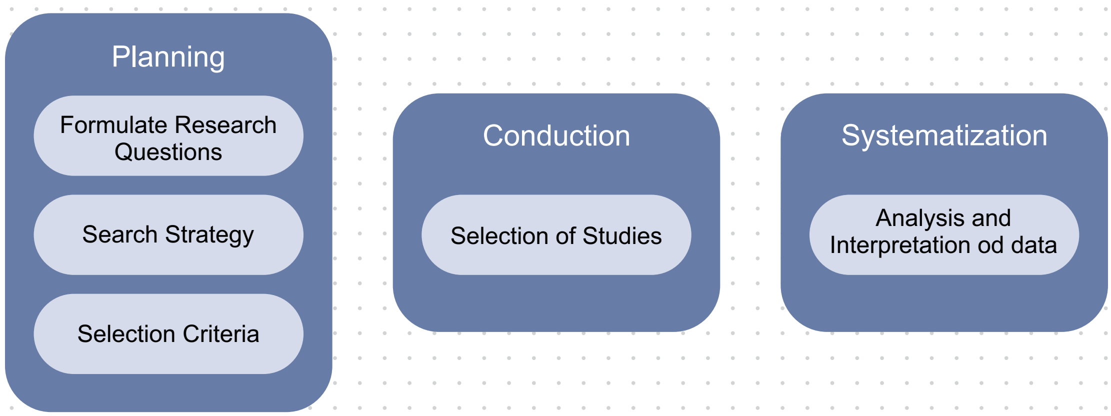
Planning

The exploratory approach required planning research questions to map methods, identify trends, and point out gaps in UAV maritime object detection studies.

Formulate Research Questions

The work is guided by seven research questions, addressing aspects of UAV-driven maritime object

Figure 1. Methodology diagram.



detection systems: RQ1: What are the primary research objectives in UAV-driven maritime object detection studies?; RQ2: What techniques enhance maritime imagery for automated analysis?; RQ3: Which deep learning architectures and computational techniques show optimal performance for maritime object detection tasks?; RQ4: What evaluation metrics and validation methodologies assess system performance?; RQ5: How extensively are UAV systems integrated into current research implementations?; RQ6: What environmental conditions and maritime contexts are primarily addressed in current research?; RQ7: How do the models perform on the defined dataset?

RQ1 aims to map the main technology domain applications. RQ2 and RQ3 analyze technical aspects, with emphasis on image processing and AI architecture. RQ4 seeks to understand performance evaluation and validation methods. RQ5 examines system integration. Finally, RQ6 and RQ7 synthesize the findings addressing application contexts.

Search Strategy and Selected Databases

The keywords used were: (learning model) AND ("classification" OR "detection" OR "segmentation") AND (aerial image) AND ("maritime" OR "boat" OR "ship" OR "swimmer").

The search was conducted in the following databases: IEEE Xplore Digital Library; ScienceDirect (Elsevier); MDPI Publications.

These databases ensure peer-reviewed quality and academic credibility. Related to time, we are looking for studies published between January 2020 and April 2025 to capture recent research developments, including both journal articles and conference proceedings in English.

Selection Criteria

Inclusion Criteria

- Studies addressing classification, detection, or segmentation of vessels or swimmers in maritime environments.
- Research incorporating UAV applications or aerial imagery analysis.
- Publications providing methodological descriptions and quantitative results.
- Peer-reviewed studies published in reputable venues (2020-2025).
- Full-text accessibility for analysis.
- Primary research contributions (excluding reviews and meta-analyses).

Exclusion Criteria

- Incomplete publications (expanded abstracts, conference posters, position papers).

- Studies lack keywords in title, abstract, or keyword sections.
- Research does not directly address maritime object detection tasks.
- Inaccessible full-text publications.
- Duplicated publications or multiple versions of same studies.
- Secondary research (reviews, surveys, opinion pieces).

Research Conduction

The initial search yielded 2,498 results, with 127 studies proceeding to full-text evaluation after title and abstract screening. As illustrated in Figure 2, publication volume increased from 8 studies in 2020 to 47 in 2024. In terms of publication venues, ScienceDirect accounted for the largest share, followed by IEEE and MDPI (Figure 3).

After applying the established criteria, 59 studies were selected for final analysis. Data extraction employed was helpful to address model architectures, evaluation metrics and preprocessing techniques.

Figure 2. Articles distribution by year.

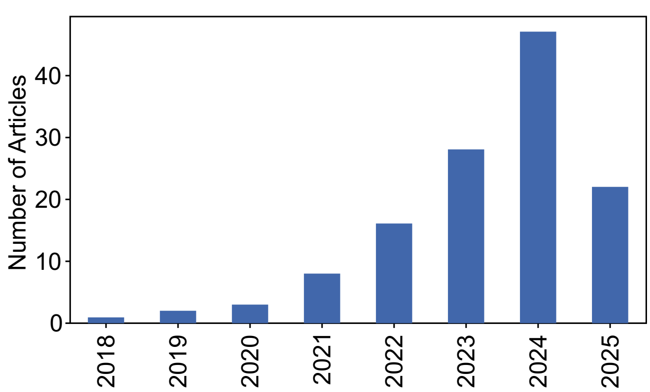
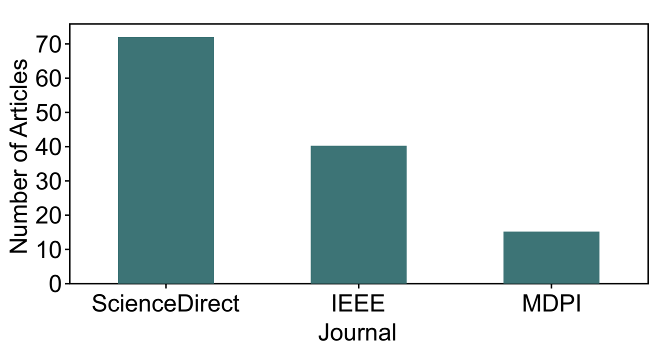


Figure 3. Articles distribution by journal.



Research Systematization

In the systematization of results, quantitative analysis was performed including frequency analysis of methodological approaches, aggregation of performance metrics and statistical analysis, temporal trend analysis of publication patterns, and comparative analysis between detection targets and environmental conditions. Qualitative synthesis involves thematic analysis of research trends, identification of methodological patterns, assessment of technological maturity levels. Data visualization and tabulation were performed by the authors using extracted information from the selected studies. All figures and tables represent original analysis and synthesis of the reviewed literature.

Results

The following sections seeks to answer the research questions, relating the found papers and their contributions on these topics.

Research Objectives Analysis (RQ1)

The research objectives focus on five main application domains (Table 1). Categories are not mutually exclusive. Articles may address multiple objectives simultaneously, resulting in overlapping classifications.

Preprocessing Techniques Analysis (RQ2)

The data composition involved public datasets (SeaDronesSee [55], Ships Dataset [56,57], MOBdrones [58]), custom-built collections, and synthetic images generated to training.

Preprocessing included resizing (640×640 or 480×480), data augmentation (flips, rotations, contrast/brightness adjustments, mosaic), color conversion, histogram equalization, noise reduction,

Table 1. Objectives and references.

Objective	References
Maritime Monitoring (89.8%)	[1–53]
Coastal Security and Surveillance (25.4%)	[3, 6, 11, 13, 15, 21–25, 44, 45, 48, 50, 54]
Beach Safety Management (23.7%)	[5, 11, 13, 18, 22, 26–29, 32, 36, 44, 46, 50]
Search and Rescue Operations (15.3%)	[3, 5, 18, 26, 27, 29, 32, 36, 46]
Environmental Protection (6.8%)	[13, 44, 50, 54]

patch extraction, anchor box optimization, and simulation of adverse weather conditions.

Annotations, whether manual or automated, followed COCO and PASCAL VOC formats, including rotated bounding boxes and segmentation masks for improved precision. Data splitting predominantly adopted the hold-out method (70/20/10 or 80/20). These steps aimed to improve training quality, reduce detection errors and increase generalization, directly impacting metrics such as mAP, Precision.

Model Architecture Analysis (RQ3)

Regarding deep learning architecture, the analysis reveals a significant dominance of the YOLO (You Only Look Once) versions, which constitutes 65.9% of the analyzed implementations. Preference is distributed among its various versions, such as YOLOv5 and YOLOv8 with most implementations (Figure 4).

Figure 4. Most used architecture.

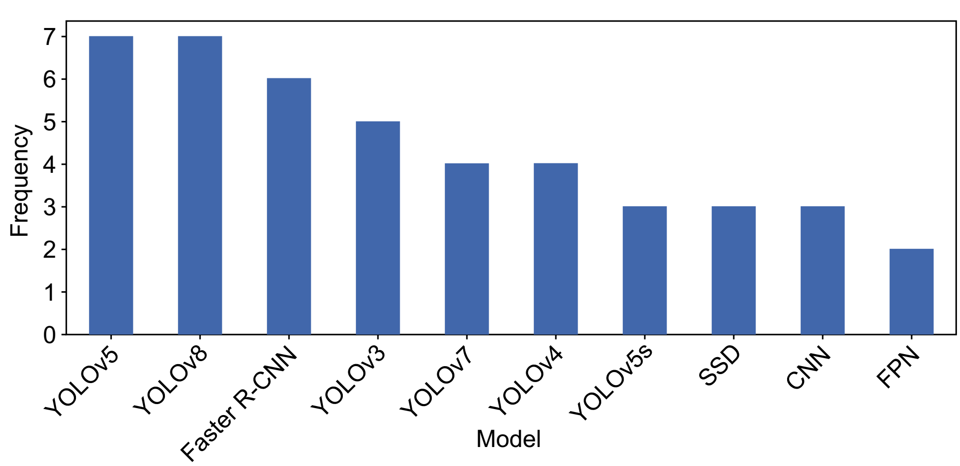


Table 2 presents Faster R-CNN as the most significant alternative. SSD and CNN are present, but seldom.

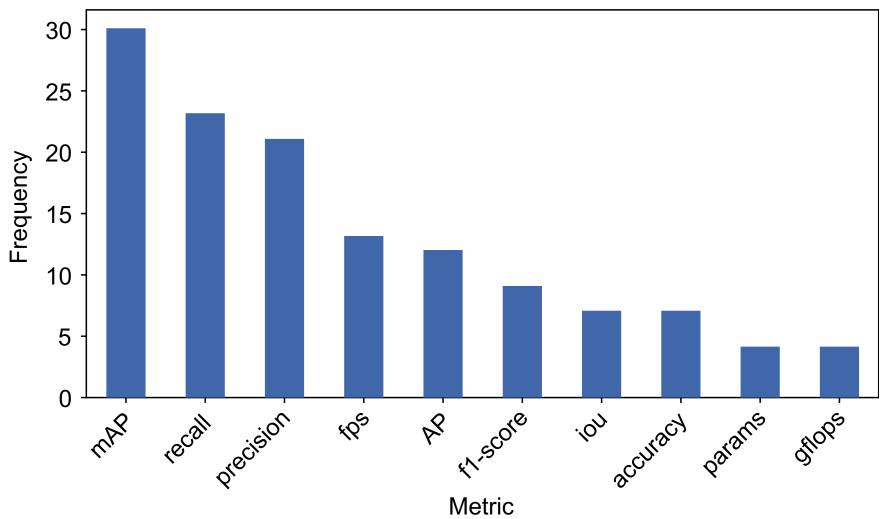
Evaluation Metrics Analysis (RQ4)

The analyzed studies reveal the use of Mean Average Precision (mAP) as the main evaluation metric followed by Recall, Precision and FPS for processing speed (Figure 5). Other commonly

Table 2. Architecture and references.

Architecture	References
YOLOv8	[4, 10, 18, 26, 34, 37, 62]
YOLOv5	[1, 4, 16, 43, 59–61]
Faster R-CNN	[1, 6, 24, 36, 61, 62]
SSD	[24, 47, 62]
CNN	[12, 27, 36]

Figure 5. Most used metrics.



used metrics include Average Precision (AP), F1-Score, Intersection over Union (IoU) and Accuracy, and computational efficiency indicators like Parameters and Gflops (Table 3).

UAV Integration Analysis (RQ5)

Although the focus of this review was on UAV-based applications, not all selected studies used images captured by UAVs. As presented in Figure 6, the UAV integration analysis shows that 74.6% of studies explicitly reported UAV use, 18.6% studies did not specify the aerial platform, and 6.8% studies employed other aerial sources (Table 4).

Environmental Context Analysis (RQ6)

The analysis of detection targets shows the distribution of research across maritime object categories. As seen in Table 5 and Figure 7, vessel detection takes the largest share, followed by combined approaches, and swimmer detection last.

Table 3. Metric and references.

Metric	References
mAP (50.8%)	[1, 2, 4, 5, 8–10, 13, 14, 17, 18, 21, 22, 24–26, 28, 29, 34, 35, 39–41, 43, 45, 54, 59–62]
Recall (38.9%)	[1, 4, 5, 10, 13–15, 20, 22, 23, 28, 30, 35, 38, 39, 41–43, 46, 50, 51, 54, 59]
Precision (35.5%)	[1, 5, 10, 14–16, 20, 23, 30, 34, 35, 38, 39, 41–43, 46, 50, 51, 54, 59]
FPS (22.0%)	[7, 9, 11, 16, 21, 24, 25, 28, 38, 41, 46, 49, 50]
AP (20.3%)	[5, 8, 10, 14, 31, 33, 36, 38, 40, 46, 47, 50]
F1-Score (15.2%)	[2, 5, 14, 20, 23, 34, 41, 42, 49]
IOU (11.8%)	[2, 6, 11, 15, 19, 24, 36]
Accuracy (11.8%)	[6, 12, 23, 34, 42, 44, 62]
Parameters (6.7%)	[7, 33, 46, 49]
Gflops (6.7%)	[7, 9, 38, 41]

Figure 6. Articles related to UAV.

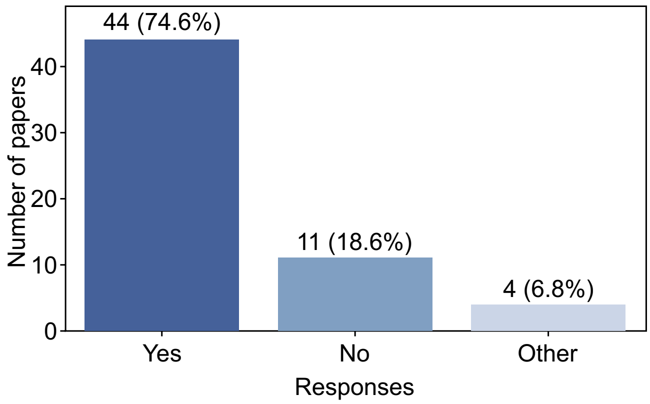


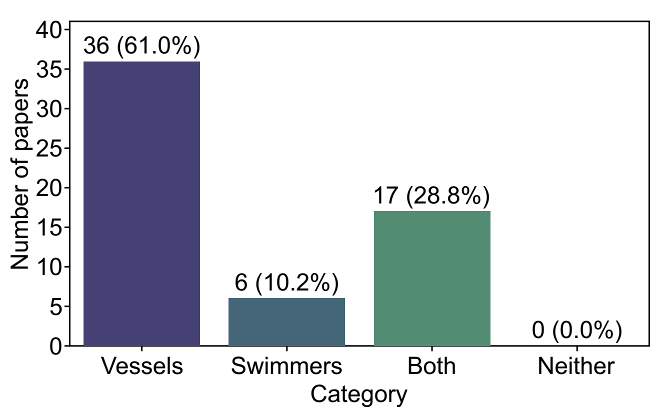
Table 4. UAV related and references.

UAV Related	References
Yes	[2–13, 15–32, 35, 36, 41, 46–50, 52, 54, 59–61]
No	[1, 33, 34, 37–40, 42, 44, 45, 62]
Others	[14, 43, 51, 53]

Table 5. Object detection target and references.

Object	References
Vessel	[1, 2, 5–8, 10–13, 15–17, 20–23, 25, 30, 31, 33, 34, 37–40, 42–46, 48, 52–54, 62]
Swimmer	[26, 27, 36, 41, 47, 61]
Both	[3, 4, 9, 14, 18, 19, 24, 28, 29, 32, 35, 36, 49–51, 59, 60]

Figure 7. Articles focused on vessels or swimmers.



Performance Analysis (RQ7)

Performance varies across datasets and detection targets, influenced by object type and environmental conditions. YOLO-based models generally provide stable results, achieving higher accuracy for vessel detection compared to swimmer detection.

In maritime-specific datasets, YOLOv8 variants have reached up to 97% accuracy in controlled environments [34]. However, detecting small objects remains a persistent challenge, with reduced accuracy observed for targets such as swimmers or distant vessels. Adverse weather conditions, including rain and haze, significantly degrade detection performance, with mean average precision dropping by 73% to 93% in synthetic datasets [1]. Nevertheless, approaches such as weather simulation and synthetic data augmentation have demonstrated improvements. The use of multi-modal data, combining visible and near-infrared imagery, enhances generalization, achieving up to 99.5% AP@0.50 for larger vessels [39]. Similarly, transfer learning from general-purpose datasets like COCO, when fine-tuned for maritime applications, has produced mAP scores of up to 67.6% across detection classes [18]. Overall, vessel detection consistently outperforms swimmer detection across different models and environmental conditions.

Discussion

This review highlights UAV-driven maritime object detection trends. YOLO dominates implementations, reflecting efficiency needs for real-time UAV operations but limiting architectural diversity. Standardized metrics (mAP, Precision, Recall) enable cross-study comparison, and steady publication growth signals field maturation. However, performance gaps between vessel and swimmer detection expose persistent challenges in small-object identification under dynamic maritime conditions.

The analysis reveals that while maritime monitoring represents the dominant research objective, the field exhibits significant overlap in application domains. This multifaceted approach reflects the practical reality that UAV-based maritime surveillance systems must serve diverse stakeholder needs, from coastal security to search and rescue operations.

Research Gaps and Future Directions

Current research exhibits significant gaps in multi-modal sensor integration, with limited exploration of weather-robust fusion techniques despite maritime environments' demanding conditions. The absence of standardized benchmark datasets complicates method comparison and performance validation across studies.

Swimmer detection research is severely underrepresented, limiting search and rescue capabilities. Real-world validation studies are scarce. Adverse weather conditions cause dramatic performance drops, highlighting robustness limitations.

A few studies suggest improvement of small debris detection, exploration of architectures beyond YOLO, and development of frameworks for object identification, these directions lack implementation specificity. The call for multimodal systems for standardizing protocols and real-time operations requires more detailed technical frameworks.

Limitations

This review's scope limitations include English-language restriction and temporal boundaries (2020-2025), potentially excluding relevant international research and foundational studies. Database selection may miss specialized maritime publications, while evaluation metric heterogeneity limits direct performance comparisons and benchmark establishment.

Conclusion

The literature review indicates that YOLO architecture models are the predominant approach for object detection and classification in maritime environments, driven by their real-time efficiency, although their dominance in the field raises questions about the overall performance across different types of objects and environmental conditions. The work also revealed some gaps in the area, such as limited articles focused on swimmer detection and limited use of multimodal approaches, which could significantly improve system robustness under adverse conditions.

Furthermore, the growth of research in the area indicates field prosperity, with the following directions suggested for future studies: improvement of small debris detection; exploration of architectures beyond YOLO; a framework for object identification; and a multimodal system for standardizing protocols and real-time operations that considers the identified performance disparities.

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Bibliometric Mapping of Human-Machine Interfaces in Autonomous and Intelligent Systems

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The growing integration of autonomous systems in industry has reinforced the demand for efficient Human-Machine Interfaces (HMIs) to ensure safe and adaptive interactions. This study presents a bibliometric analysis of 99 publications (2015–2025) on supervisory interfaces, using Scopus data and tools such as VOSviewer and Bibliometrix. The results revealed six main clusters, centered on terms like human-machine interface, process control, machine learning, and decision-making. The analysis highlights the leadership of China, the United States, and India, while showing the absence of Brazilian contributions. A marked rise in publications occurred after the COVID-19 pandemic, although gaps persist in applied studies involving biosystems.

Keywords: Bibliometric Analysis. Combined Technologies. HMI. Process Control.

Abbreviations: HMI, Human-Machine Interface. SCADA, Supervisory Control and Data Acquisition. AI, Artificial Intelligence. PLC, Programmable Logic Controller. Sustainable Development Goals, SDG.

The integration of humans and intelligent machines is a central feature of industrial transformation. In Industry 4.0, automation plays a key role in optimizing processes, reducing human effort, and increasing productivity [1]. Autonomous systems that work independently with the help of mechanical, control, computing, and communication technologies have emerged as a natural development [2].

Despite their potential for efficiency and scalability, these systems still require human supervision through safe, understandable, and reliable interfaces. Human-Machine Interfaces (HMIs) are essential for mediating interactions in automated environments and supporting monitoring, control, and decision-making [3].

Autonomy has gained strategic importance across various sectors, including biotechnology, chemical engineering, and defense. Reports, such as The Status of Autonomy in the Department of Defense Unmanned Systems, underscore this importance [4]. However, systematic study of HMI development in autonomous systems remains scarce, especially after the COVID-19 pandemic, and given the growing interest of industrialized nations. In Brazil, research and investment in this area are still limited [5].

Understanding the evolution of HMI research is key to identifying trends, gaps, and future directions. These insights support the development of safer and more effective interfaces that meet the requirements of Industry 4.0.

This study aims to map and analyze the scientific production on Human–Machine Interfaces (HMIs) in autonomous and intelligent systems between 2015 and 2025, using Scopus data. Through the application VOSviewer and Bibliometrix (via Biblioshiny), it aims to identify thematic trends, international collaboration networks, and under-researched areas, focusing on the positioning and contributions of the Brazilian context within the global scenario.

Materials and Methods

Database Survey

A quantitative and descriptive bibliometric study was carried out to collect data from articles in the Scopus database. The platform was searched using Boolean operators with the following terms: “supervisory interface” OR “HMI” OR “supervisory control system” AND “autonomous

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systems" OR "intelligent systems" OR "smart process", "bioreactor" OR "biological reactor" OR "process control", and "data interpretation" OR "data visualization". Results were filtered by language (English), publication period (2015-2025), document type (articles and reviews), and subject areas (Computer Science, Engineering, and Chemical Engineering). After applying these criteria, 99 documents were selected, and their citation information, bibliographic data, abstracts, and keywords were exported in .csv format for bibliometric analysis.

Bibliometric Tools

After data collection, the .csv file was processed using two different software tools, both designed for bibliometric analysis: VOSviewer and Bibliometrix. The first software used was VOSviewer. It is a free tool for building and visualizing bibliometric networks between user-defined elements [6].

In VOSviewer, the following parameters were set when importing the data: co-occurrence check with full count, including all keywords. A minimum of four occurrences was required for a keyword to be included in the map. The threshold was chosen because three occurrences resulted in too many terms, while five returned too few. Using these parameters, 49 keywords were identified and selected to avoid redundancy on the map. After a visual inspection, 47 keywords were manually selected.

Bibliometrix, on the other hand, is an R-based package that integrates with a web interface called Biblioshiny [7], designed for the analysis of scientific mapping data [8]. To use it, the R programming language and the RStudio IDE were installed. The Bibliometrix library was then loaded, and the .csv data imported. After the setup, Biblioshiny was launched to generate the necessary graphs and maps.

Unlike VOSviewer, the graphical settings in Biblioshiny can be adjusted individually for each visualization and changed during the analysis to include more or less data. Relevance maps were generated using all keywords, comparing the most frequent terms over 2015–2021 and 2022–2025. Additionally, charts were created to show the top five countries with the highest research output and the number of publications per year.

Results

In order to examine keyword co-occurrence, thematic clusters, temporal trends, and geographic distribution, we used the VOSviewer and Bibliometrix tools to generate maps and graphs. Thus, the data presented below represent a structured interpretation of the evolution of research on human-machine interaction and supervisory interfaces over the last decade, demonstrating a systematic evaluation of the information obtained.

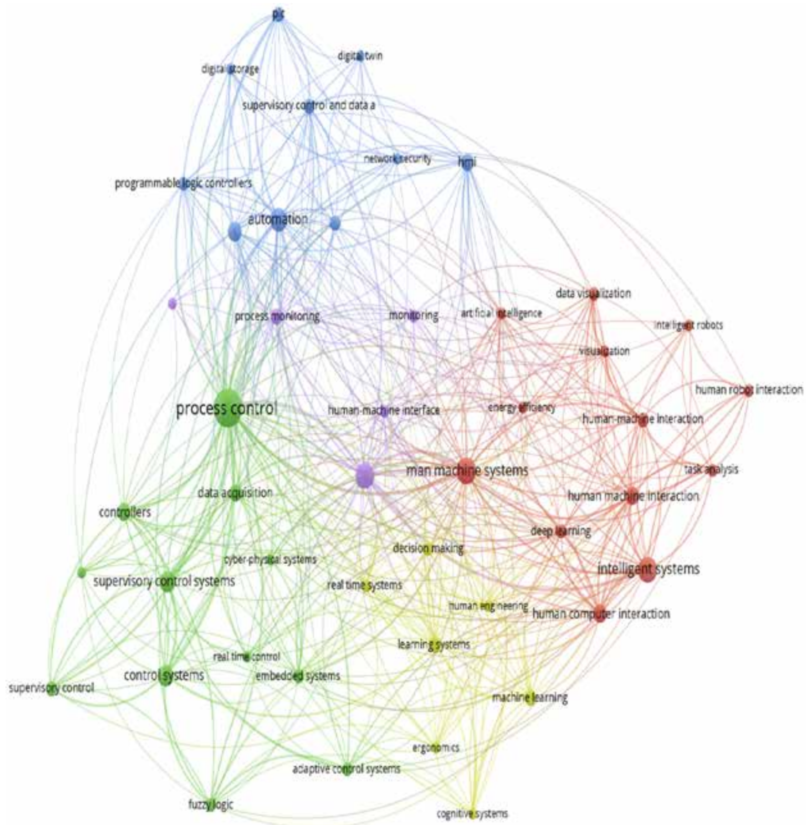
Analysis using VOSviewer

VOSviewer generated a bibliometric map based on articles extracted from the Scopus database, organized by similarity and term frequency (Figure 1). Six main clusters were identified, interconnected by central nodes such as "human-machine interface", "process control", "machine learning", and "decision making", which structure the main relationships between the topics.

The term "human-machine interface" occupies a central position in the diagram, linked to technical areas such as "SCADA", "PLC", and "digital twin", as well as cognitive aspects such as "learning systems" and "data visualization". The centrality of the map highlights its role as a link between human cognition and automated systems. Adaptive interfaces tend to improve situational awareness and supervisory performance [9], with multilevel delegation being a promising model in this context [10].

The study suggests that future systems should go beyond data display to act as active agents in decision making, risk anticipation, and contextual adaptation, positioning humans more

Figure 1. VOSviewer bibliometric map showing 5 different clusters separated by colors and their connections with other keywords.



as supervisors rather than operators, mainly in complex environments such as biotechnology and bioprocesses, where real-time interpretation is essential.

The term "process control" is the largest node in the graph, maintaining its relevance despite advances in intelligent systems. It is directly linked to technologies such as "supervisory control systems", "embedded systems", and "real-time control", confirming its technical core role. In biotechnology, its presence reinforces the need for robust and responsive control systems in the face of biological variability and production conditions, paving the way for interfaces that enable more precise control in dynamic bioprocesses.

"Machine learning" appears as a vector of system evolution, linked to terms such as "deep learning", "learning systems", and "decision making". Its peripheral but highly connected position indicates an emerging field with strong potential for adaptive integration [11], notably in dynamic contexts involving continuous learning [12].

Meanwhile, "decision making" serves as a bridge between technical and cognitive approaches, relating to "real-time systems", "human-machine interface", and "human-computer interaction". It demonstrates that supervision goes beyond data visualization; it also requires interpretation and action [13]. In the context of Brazilian biotechnology, the connection suggests the development of interfaces compatible with edge devices that support autonomy even in environments with limited data or infrastructure.

Taken together, these four terms reflect a trend in the literature: the strengthening of intelligent supervisory models, centered on the operator interface and supported by "process control". The data also highlight innovation in biotechnology and bioprocesses, with a focus on Brazil, through the development of adaptive and predictive "human-machine interfaces" capable of operating in uncertain environments, integrating biological data, and supporting real-time strategic decision-making.

Analysis using Bibliometrix

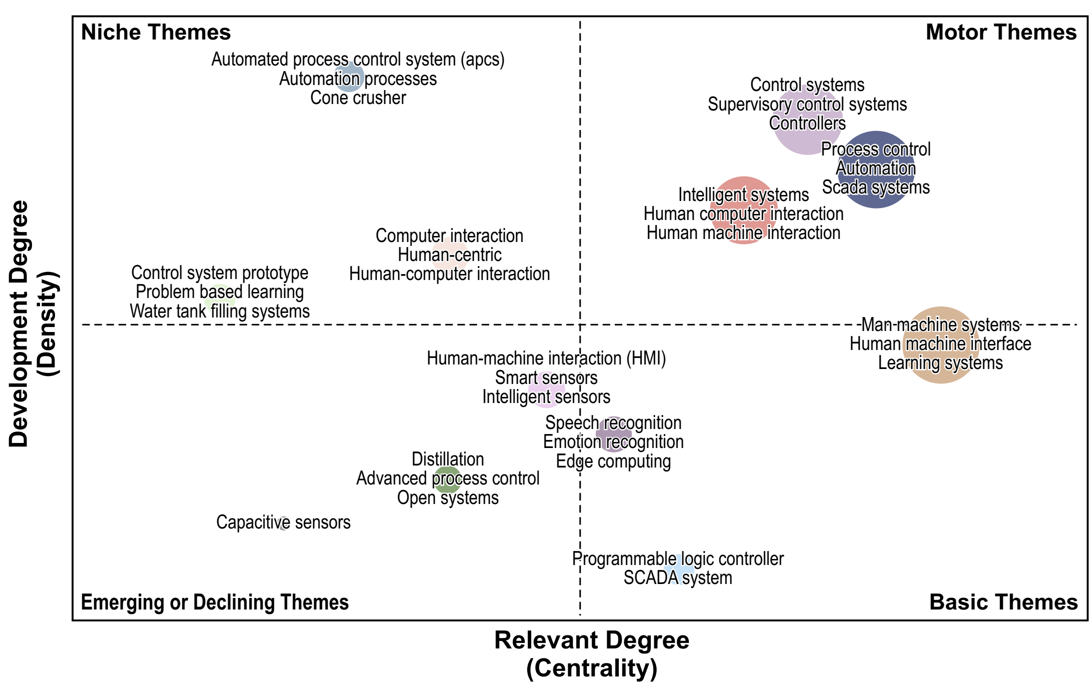
Topic Relevance Map

The thematic map generated by Bibliometrix distributes topics across four quadrants: "Motor Themes", "Basic Themes", "Niche Themes", and "Emerging or Declining Themes" (Figure 2). In this case, terms such as "process control", "supervisory control systems", "automation", and "SCADA systems" appear in the upper right quadrant, indicating high density and centrality, which are well-developed and fundamental topics in the field. The position of these terms reinforces the historical dominance of technical control in supervisory systems. This is due to the essential role of supervision in the use of interfaces for task control, enabling rapid decision-making and high-level language instruction, supported by tools such as simulations, which, while not inherent to automation, are critical at scale [14]. Demonstrate the importance of supervisory systems in process control.

The group of terms such as "human machine systems", "human machine interface", and "learning systems" are in transition between the Basic and Motor quadrants, suggesting that although initially structural concepts, they become central as adaptive processes. This growth is linked to systems that learn from human–machine interaction data, using self-adaptive mechanisms inspired by collective behavior. Techniques such as swarm intelligence are beginning to be applied to optimize decision-making and personalize care through adaptive content scheduling and real-time data display adjustments [15]. It is used to facilitate interaction with the interfaces, even if the user is not used to complex systems.

Terms such as "emotion recognition", "smart sensors", and "edge computing" appear with a loss density, located in the lower quadrant. It may indicate that these areas, while still incipient,

Figure 2. A relevance map that organizes keywords into four sectors to show their importance and use in articles.



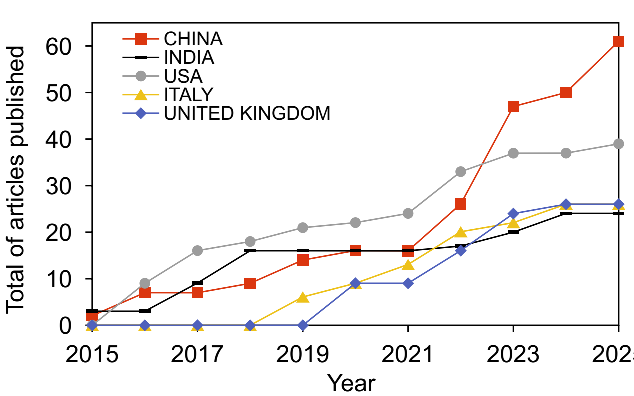
are emerging as relevant issues, particularly in the context of more sensitive and responsive interfaces. Their position invites reflection on the rise of approaches centered on human perception and behavior, particularly in light of predictions that computing will become invisible, integrated into all spaces, and put the user at the forefront, to make the experience more intuitive, contextual, and personalized [16]. This underscores the importance of autonomous systems and easy-to-use control-operated supervisory interfaces for new industries, where innovation and efficiency are essential.

Finally, the isolated position of "programmable logic controller" and "SCADA system" in the lower-right quadrant suggests that, despite their historical importance in once serving as the central control unit in industrial processes [17], these topics have not recently experienced the same pace of innovation as other topics, indicating a stabilization or potential need for conceptual updating.

Scientific Production Over Time

A temporal examination of scientific production from 2015 to 2025, based on Scopus data, revealed significant trends (Figure 3). The country evolution chart shows that China, the United States, and India were the main producers, with a sharp increase after 2021. This growth may be a

Figure 3. Country production over time in a graph with countries separated by color.



strategic response to the need for new autonomous control and supervision methods, especially after the COVID-19 pandemic, which highlighted the importance of automation for industrial resilience [1]. The rise of these countries, especially those with a strong industrial tradition, suggests a strategic response to the need for new autonomous control and supervision methods to replace human systems that were compromised by the limitations of physical distance [18].

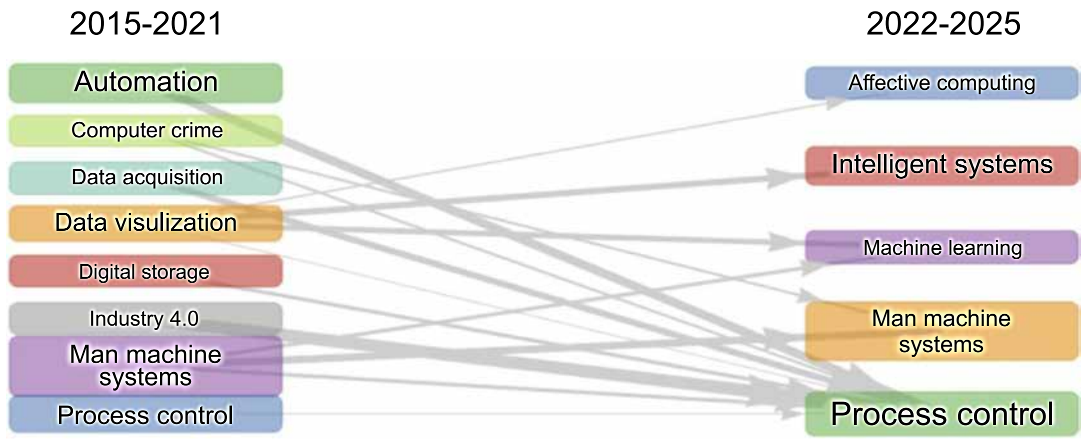
In addition, the absence of Brazil among the main producing countries, at least in the articles filtered in the research, raises questions about the level of national investment in applied research on the topic, possibly due to the computational cost demands [5], or even due to a possible dispersion of scientific production in areas not directly indexed or focused on other scientific perspectives. Such results show a gap area to be explored, even with little investment in the field, especially for biotechnological industries.

In addition to this perspective, there is also the evolution of keywords between the periods from "2015 to 2021" and from "2022 to 2025" as shown in Figure 4.

These reflect the major shifts in thematic focus. Terms such as "automation", "data acquisition", "Industry 4.0", and "data visualization" have recently given way to topics such as "machine learning", "affective computing", and "intelligent systems". This transition is related to a shift from structural technologies to those with greater cognitive and adaptive capacity [14], in line with the growing need for more humanized and context-aware systems. The prominence of "affective computing", for example, suggests, as said before, an emerging interest in reading the emotional states of the operator, which is fundamental for decision-making based not only on technical variables, but also on behavioral ones [15].

By enabling precise control and process optimization, these interfaces reduce energy and resource use, minimize production and supply chain waste, improve safety, and lower environmental risks, thus aligning with key United Nations

Figure 4. Thematic evolution shows the evolution of the article's focus over time.



Sustainable Development Goals (SDGs) such as SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) [19]. Although focused on bibliometric assessment, this study offers insights into integrating supervisory HMIs with HPC, intelligent sensing, and sustainable mobility solutions in the field.

Conclusion

The bibliometric research conducted using VOSviewer and Bibliometrix between 2015 and 2025 confirms a consistent growth in research on human-machine interfaces in autonomous and intelligent systems, with a stronger focus in industrialized countries. Examination of 99 publications enabled us to identify six main clusters, centred on terms such as 'human-machine interface', 'process control', 'machine learning', and 'decision making'. Co-occurrence, geographical, and temporal distributions revealed an increasing trend towards the integration of artificial intelligence, supervision, and decision-making, as well as a notable surge in studies following the onset of the pandemic. However, significant gaps remain, such as low application in biosystems and the absence of Brazilian contributions, highlighting the need for greater national investment. Technological evolution points to a transition from structural to cognitive and adaptive approaches. This reinforces the importance of multidisciplinary research to meet the demands of Industry 4.0, particularly in emerging economies.

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SARA: An LLM-Based Approach for Systematic Literature Review with a Use Case on Classical–Quantum Integration for Secure Communication

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This work presents SARA (Semi-Automated Review and Analysis System), an approach that integrates Large Language Models (LLMs), topic modeling, and semantic search to support Systematic Literature Reviews (SLRs). As a use case, SARA was applied to the domain of integration between classical networks and secure quantum communications, covering Quantum Key Distribution (QKD) and Post-Quantum Cryptography (PQC). The system performed deduplication, pre-selection, categorization, and ranking of articles, prioritizing publications with higher potential for scientific contribution. The results indicate a predominance of studies on QKD, followed by PQC and hybrid approaches, with emphasis on telecommunications, IoT, and critical systems. SARA proved effective in identifying publications aligned with the researcher's queries as well as conceptually related studies, demonstrating its potential to optimize SLR processes in emerging technological areas.
Keywords: Systematic Literature Review. Topic Modeling. Semantic Search. LLMs. Quantum-Safe Communications.
Abbreviations: SARA, Semi-Automated Review and Analysis System. LLM, Large Language Model. QKD, Quantum Key Distribution. PQC, Post-Quantum Cryptography. SLR, Systematic Literature Review. NLP, Natural Language Processing.

The volume of scientific publications has grown exponentially in recent decades, driven by digital dissemination and broad accessibility to specialized databases. This trend makes the execution of Systematic Literature Reviews (SLRs) increasingly challenging, as they demand time, methodological rigor, and substantial human effort. With the advancement of Large Language Models (LLMs), such as GPT and its variants, a growing number of studies explore their use to optimize different phases of the SLR process [1]. Hybrid approaches that combine LLMs with human review have been shown to reduce screening and data extraction time while maintaining high accuracy [2], whereas techniques based on contextual embeddings and deep learning have demonstrated effectiveness in pre-classification and thematic clustering of articles, thereby accelerating the initial screening stages [3].

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In recent years, the volume of publications related to quantum technologies applied to information security has grown rapidly, following the maturation of prototypes and the execution of field tests, such as the example of the Rio Quantum Metropolitan Network [4]. This progress is driven both by the race to enable unbreakable communications and by concerns about the socalled "quantum apocalypse," the possibility that sufficiently powerful quantum computers could compromise currently deployed cryptographic algorithms [5]. Among the approaches to mitigate this risk, two stand out: (i) Quantum Key Distribution (QKD), which uses a quantum channel to securely share cryptographic keys between two parties, leveraging fundamental principles of quantum mechanics and relying on a classical channel for authentication [6]; and (ii) Post-Quantum Cryptography (PQC), which employs encryption algorithms based on mathematical problems considered hard even for quantum computers [7]. Although distinct in their implementation, QKD and PQC pursue the same goal: ensuring that communication remains secure against adversaries equipped with quantum capabilities.

In this context, the need for tools capable of performing pre-selection, classification, and ranking of publications based on semantic criteria becomes evident. This study proposes and applies a semi-automated approach to SLR, which we designate as SARA (Semi-Automated Review and Analysis System). SARA enables the initial screening and categorization of relevant scientific articles by integrating Natural Language Processing (NLP) techniques with LLMs. For this use case, our focus lies on three main objectives: (i) the integration of classical systems with quantum technologies, including PQC, QKD, or both; (ii) the modeling of major recurring topics in the field; and (iii) the semantic retrieval of the most relevant articles, prioritizing those with the greatest potential for scientific contribution.

Related Work

Research on computational methods to support SLRs has evolved rapidly, following the progress of NLP techniques, deep learning, and, more recently, LLMs [8]. Existing approaches vary in scope and degree of automation, ranging from workflows based on traditional machine learning to interactive systems with semantic understanding capabilities. Despite significant advances, few studies fully integrate researcher-driven question-oriented ranking mechanisms, topic modeling, and contextual semantic search—key elements for prioritizing the most relevant publications in complex domains.

As shown in Table 1, Pham and colleagues [9] present a semi-automated workflow combining Random Forest, SVD, LDA, and embeddings, reducing the screening workload by 55–63%. Tsang and Lee [10] combine BERT embeddings, BERTopic, and semantic retrieval, enabling interactive query-based filtering. Ye and colleagues [2] apply bibliometric analysis and topic modeling to map research trends, but without embedding-based semantic retrieval. Ramesh and Sanampudi [11] review active learning for screening, with human feedback influencing prioritization.

Finally, Galli and colleagues [8] integrate LLMs for summarization, classification, and question-guided ranking, combining semantic search with topic modeling.

The SARA approach distinguishes itself by integrating four key elements: LLMs, question-oriented ranking, topic modeling, and semantic retrieval. Unlike prior works as Galli and colleagues [8], SARA links researcher queries directly to corpus themes, enabling dynamic score adjustment and more accurate prioritization, while streamlining pre-selection to reduce human effort. As a toy example for demonstrating SARA, the case study on Classical–Quantum Integration for Secure Communication was based on prior studies on edge–quantum frameworks [12], hybrid cryptographic protocols [13,14], and QKD co-simulation [15]. We present SARA's architecture, techniques, and implementation, providing a detailed description of SARA's architecture, the techniques employed, and the implementation process.

Table 1. Comparison of related works.

Reference	Year of publication	Use of LLMs	Question Oriented Ranking	Topic Modeling	Semantic Search
[9]	2021	No	No	Yes	Yes
[10]	2022	No	Partial	Yes	Yes
[11]	2022	No	Partial	No	Partial
[2]	2024	No	No	Yes	Partial
[8]	2025	Yes	Yes	Yes	Yes
SARA	2025	Yes	Yes	Yes	Yes

Material and Methods

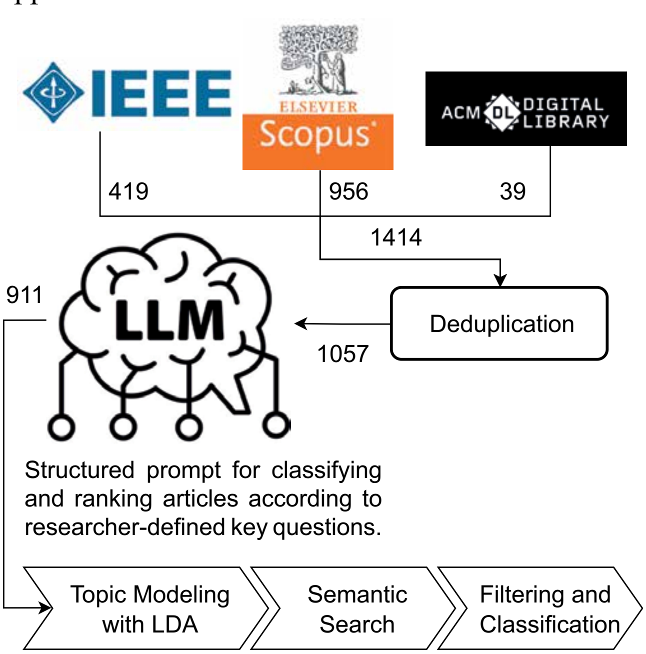
The methodology adopted in this study is designed to conduct an SLR in a semi-automated manner, aiming to reduce human effort in the initial stages of article screening and organization.

The methodological workflow comprises four main stages: (i) data collection and deduplication; (ii) LLM-based pre-selection; (iii) topic modeling; and (iv) semantic search (Figure 1). This process, referred to as SARA, spans from the initial deduplication to the final prioritization of articles, incorporating topic modeling and question-guided semantic ranking.

Search String Construction

As a preliminary step, a standardized search string was developed to maximize the relevance of results across the three databases consulted (IEEE Xplore, Scopus, and ACM Digital Library), ensuring the retrieval of publications aligned with the research scope. The query was constructed using Boolean operators applied to the abstract field:
(("Quantum Key Distribution" OR "QKD" OR "Quantum Cryptography" OR "Quantum Key Exchange" OR "Post-Quantum Cryptography" OR "PQC" OR "Quantum-Resistant Cryptography" OR "Quantum-Safe Cryptography") AND ("integration" OR "interoperability" OR "migration" OR "framework" OR "compatibility" OR "communication protocol"))

Figure 1. Methodological workflow of the SARA approach.



The process begins with corpus deduplication, followed by automatic evaluation of the abstracts through a structured prompt, topic modeling with LDA, and semantic search. In the final stage, articles are filtered, classified, and ranked based on the answers to the researcher's questions.

The first set of terms refers to the target technologies of this review: QKD, PQC, and terminological variations associated with quantum and post-quantum cryptography; while the second set encompasses concepts related to system integration and interoperability, ensuring that the retrieved results included studies addressing both the technological aspects and their application in communication architectures.

The results obtained from the three databases were exported in CSV format, consolidated, and subjected to a deduplication process based on title, year, and DOI matching (when available, as not all articles provided this identifier), resulting in a total of 1,057 articles.

Automated Pre-selection with the LLM (GPT)

A structured prompt was designed for the automatic evaluation of abstracts, covering five criteria: (1) technologies mentioned — PQC, QKD, both, or none; (2) integration with classical networks — real implementation, simulation, conceptual proposal, or no integration; (3) application or prototype — presence and description; (4) technical challenges — quantitative, qualitative, or both; and (5) application domains — up to ten possible areas.

Each criterion was assigned a specific score, with items (1) and (2) defined as exclusion criteria—if both are classified as "None," the article receives a score of –10 and is automatically excluded from the SLR. Items (3), (4), and (5), in turn, are classificatory: if the abstract explicitly reports an application, technical challenge, or application domain, 1 point is assigned for each occurrence. Finally, the articles are ranked based on the sum of scores, resulting in a reduced set of 911 studies with potential relevance.

Topic Modeling (Latent Dirichlet Allocation – LDA)

For the thematic organization stage, the LDA algorithm was employed [16], aiming at the automatic detection of predominant topics within the set of pre-selected articles. The abstracts are pre-processed and subsequently submitted to LDA modeling, which enables the identification of latent topics and the clustering of studies into representative macro-themes of the field [17].

Semantic Search Based on Embeddings

After the topic modeling stage with LDA, the results are used to guide the retrieval of semantically relevant documents. For this task, the pre-trained model all-MiniLM-L6-v2, provided by the Sentence-Transformers library, is adopted to convert both abstracts and researcher queries into dense vector representations. The similarity between documents and queries is computed using the cosine metric, enabling the identification of related publications even in the absence of exact lexical matching [18,19].

To enhance retrieval quality, each textual representation was enriched with complementary information automatically extracted by an LLM (ChatGPT-4), incorporating essential aspects such as the application, the type of technology addressed (PQC, QKD, or both), and the proposed level of integration (real, simulated, or conceptual). This semantic enrichment increased the model's ability to capture contextual nuances, resulting in more accurate recommendations aligned with the objectives of the review.

The complete SARA workflow, from the initial deduplication to the final prioritization of articles is presented in Figure 1, highlighting the stages of topic modeling and question-guided semantic ranking, along with semantic search. The next section presents the results obtained through the application of this workflow, discussing both the performance of individual stages and the overall contributions of the system to conducting Systematic Literature Reviews in the domain of QKD–PQC integration.

Results and Discussion

The application of the SARA approach led to the identification and categorization of a significant set of articles distributed across the technologies considered in this review: QKD, PQC, and hybrid approaches combining both, with the prerequisite of integration into classical networks, that is, the infrastructure and technologies currently in use.

As shown in Figure 2, a predominance of publications exclusively related to QKD was observed (497 articles), followed by PQC (306 articles), and, to a lesser extent, studies addressing QKD and PQC simultaneously (71 articles). This distribution highlights not only the more advanced stage of the literature on QKD but also the growing, albeit still limited, exploration of hybrid solutions integrating both technologies—an aspect particularly relevant to this research, given its focus on secure integration strategies between classical and quantum systems.

The analysis of application domains (Figure 3) shows a predominance of the telecommunications and 5G sector, reflecting the relevance of QKD and PQC for securing high-capacity and low-latency channels. Next, IoT/Edge, government/defense, data centers/cloud, and satellite-based systems stand out, evidencing the interest in strengthening the security of critical networks and sensitive infrastructures. Areas such as blockchain/DLT, industrial systems, the financial sector, and connected vehicles also indicate the broad potential for adopting these technologies within the digital ecosystem.

Figure 2. Distribution of the identified articles by technology: QKD, PQC, and hybrid approaches (QKD+PQC).

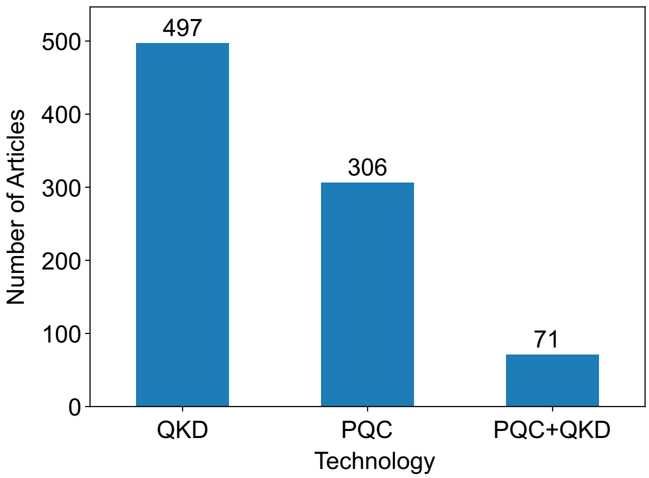
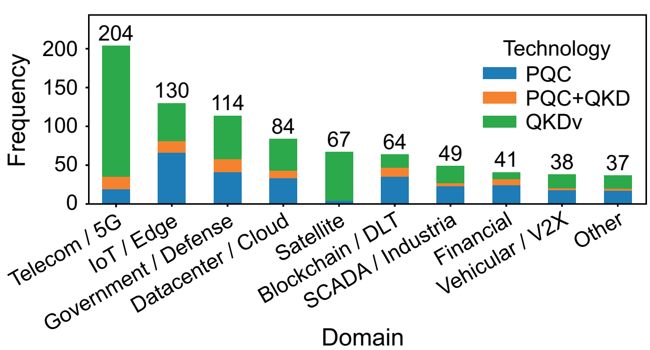


Figure 3. Distribution of articles by application domain of QKD and PQC technologies.



To evaluate the ability of the SARA approach to identify publications aligned with specific researcher queries, the following question was formulated: “What research applies quantum key distribution (QKD) or post-quantum cryptography (PQC) in 5G or telecommunications networks?”. The semantic search, using vector embeddings and cosine similarity calculation, returned a set of articles ranked according to their semantic proximity to the query. Figure 4 shows the two-dimensional projection (PCA) of this vector space, where blue points represent the articles selected as most relevant, and the red point indicates the vector position of the query within the same space. Gray points correspond to non-selected articles. This result demonstrates that SARA not only locates publications that share terms with the query but also those that exhibit conceptual relationships even with different vocabularies, assigning a quantitative degree of similarity that enables the prioritization of the most pertinent readings.

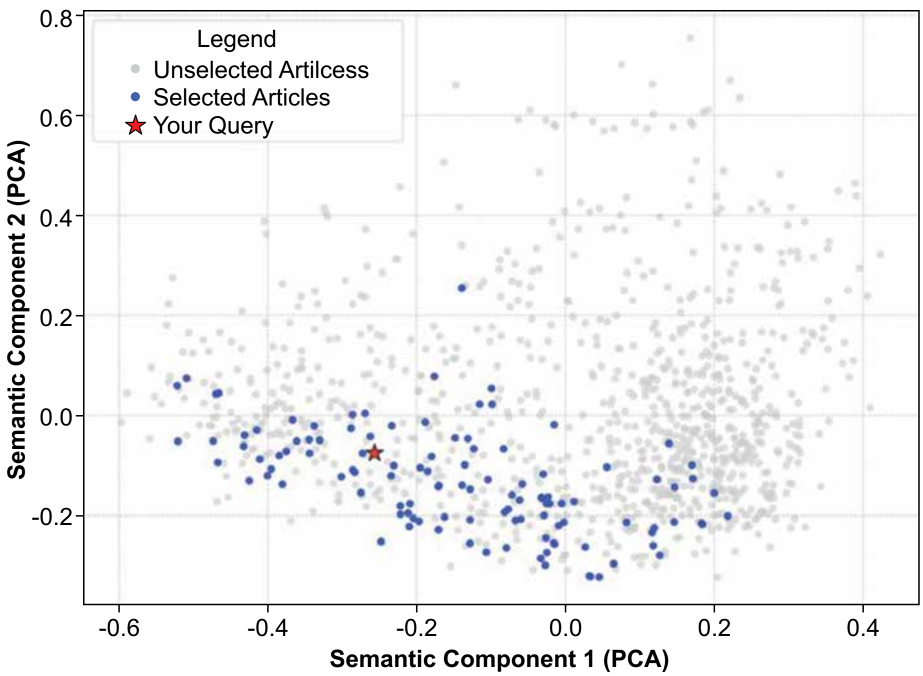
In summary, the results confirm that SARA effectively integrates topic modeling, semantic enrichment, and question-guided ranking, optimizing the selection and prioritization of articles in SLRs. The system demonstrated the ability to retrieve publications aligned with queries and to identify conceptually related studies even in the absence of lexical matching. The predominance of telecommunications and 5G underscores the relevance of QKD and PQC for the security of critical networks, while hybrid solutions emerge as a promising field. These findings consolidate SARA as a useful tool for research in emerging technological domains.

Conclusion

This work presented the SARA approach, a semi-automated methodological workflow to support SLRs, integrating topic modeling, semantic enrichment, and question-oriented ranking, with a focus on the domain of integration between classical networks and secure quantum communications (QKD and PQC). The application of SARA demonstrated that combining NLP techniques with LLMs can significantly reduce human effort in article screening and prioritization while maintaining high relevance in the results. The analyses showed that, in addition to retrieving publications directly aligned with the researcher’s queries, the system is capable of identifying conceptually related studies even in the absence of coinciding terms, an essential aspect in areas with diverse and rapidly evolving technical terminology.

The main contributions are: (i) integrating topic modeling with semantic search for corpus organization; (ii) leveraging LLM-based enrichment to enhance retrieval; and (iii) enabling dynamic question-driven ranking to guide

Figure 4. Two-dimensional projection (PCA) of the vector space resulting from the semantic search for the query “What research applies quantum key distribution (QKD) or post-quantum cryptography (PQC) in 5G or telecommunications networks?”.



Blue points represent the articles selected as most relevant, gray points indicate non-selected articles, and the red star corresponds to the query position in the semantic space.

review focus. The study further underscores the relevance of QKD and PQC for critical sectors, particularly telecommunications, IoT, and hybrid systems.

As future work, we propose: (i) expanding the analyzed dataset by incorporating multiple indexed sources and gray literature; (ii) exploring alternative embedding architectures and retrievalaugmented generation (RAG) models to improve semantic search precision; (iii) incorporating quantitative evaluation metrics such as precision, recall, and F1-score to measure performance objectively; and (iv) adapting SARA to other scientific domains, validating its generalization and comparing it against traditional SLR approaches.

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