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Volume 9 • Number 4 **SUMMARY** *April 2026*

Original Articles

Original Case Study

Systematic Review

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COVER: Figure 6. Hydrogen bonding interactions PEG-NFC. Investigation of The Use of PEG as a Compatibilizer in Nanocellulose Reinforced PLA Composites by Henrique Lucas Nao Horiuchi et al. J Bioeng. Tech. Health 2026;9(4):307.

Stochastic Degradation Modeling of a Peristaltic Pump in a Biomedical Blood Autotransfusion System

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This study compares two stochastic models, Brownian Motion with Drift and the pure Wiener Process, applied to the degradation of a peristaltic pump used in a biomedical device. Failure was defined as the reduction of flow rate below a critical threshold required for safe operation. Simulations showed that the Wiener Process consistently produced higher time-to-failure (TTF) values across all scenarios, with larger differences under low and moderate variability ($\sigma = 0.05$ and $\sigma = 0.3$) and smaller differences under high variability ($\sigma = 0.8$). The observed effect results from the deterministic component in Brownian Motion with Drift, which accelerates average degradation, while the Wiener Process is driven solely by random fluctuations, allowing greater variability in failure time. Findings indicate that, in biomedical applications, selecting an appropriate degradation model is crucial for accurate lifetime predictions and predictive maintenance planning, particularly in low-variability environments. Future work should integrate stochastic degradation models with statistical monitoring techniques to improve early fault-detection accuracy and enhance the robustness of lifetime estimation under real operating conditions.

Keywords: Stochastic Models. Degradation. Peristaltic Pump. Predictive Maintenance. Wiener Process. Brownian Motion with Drift.

Autotransfusion devices play a crucial role in the global healthcare setting, primarily because they reduce patient blood loss and concentrate red blood cells for reinfusion, thereby minimizing the need for allogeneic blood transfusions [1]. The effective operation of these devices requires integrating multiple components, such as a centrifuge for blood separation and a peristaltic pump for fluid transfer in different directions, as in the case of the AutoLog system, according to the device's user manual. It is noteworthy that the primary requirements for autotransfusion devices are to prevent contamination of the patient's blood and to ensure precise control of the flow rate of the fluids involved [2].

Given these requirements, the peristaltic pump is well-regarded for meeting them, as it exhibits characteristics that ensure high reliability, such as the absence of direct contact between the pump mechanism and the system fluid, high flow rate accuracy, and ease of maintenance. These features demonstrate its effectiveness in the development of biomedical equipment [3].

Peristaltic pumps, also classified as infusion pumps, are essential for the operation of autotransfusion devices. In this regard, it is important to highlight the importance of maintaining these devices, as their failure may lead to severe patient complications, including venous spasms, pulmonary edema, and thrombophlebitis [4]. In this context, predictive maintenance is characterized by the continuous monitoring of critical operational parameters of equipment [5], providing essential data for decision-making aimed at preventing complete operational failure and thereby ensuring device reliability [6]. For this reason, condition-based maintenance is considered the most effective approach for peristaltic pumps [7].

In parallel with maintenance strategies, degradation models serve as a valuable tool for enabling more efficient asset management, contributing to both resource optimization and safety [8], given their capability to represent how

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a system deteriorates or evolves, allowing the prediction of failures and degradation [9]. This, in turn, can help reduce uncertainties in decision-making and future projections [10], as well as improve system reliability and durability [11].

It is possible to identify the Brownian motion with drift [12] and the Wiener process [13] in the context of degradation models. Brownian motion is characterized as a stochastic model that simulates the degradation of a system or variable over time, incorporating a directional trend [14]. In contrast, the Wiener process is a stochastic model that describes system degradation in a purely random manner over time [15]. Both models can be applied to the analysis of fluid flow in a peristaltic pump.

This study aims to develop, simulate, and compare the two presented stochastic models to predict the time-to-failure (TTF) of peristaltic pumps in autotransfusion devices, and to contribute to understanding the application of degradation models in the context of biomedical equipment.

Materials and Methods

The peristaltic pump is a mechanical device used in a wide variety of biomedical equipment, including autotransfusion systems, due to its ability to move fluids in a controlled manner while minimizing direct contact with moving parts, thus ensuring the integrity of the biological fluid. This study focuses on analyzing the gradual wear of the pump's mechanical components, which can reduce operational performance and lead to eventual failure. To model the pump's degradation process, two stochastic methods were compared: Brownian Motion with Drift, which incorporates a deterministic trend associated with the average wear rate, and the pure Wiener Process, which considers only the random component of the phenomenon, without a defined trend. This comparison aims to identify which approach more realistically represents the degradation evolution of the peristaltic pump.

The degradation model based on Brownian Motion with Drift describes the wear evolution as the sum of a deterministic component and a random term. In this way, the drift represents the average degradation rate over time, while the stochastic term models the inherent random fluctuations of the process, such as variations in friction or minor operational irregularities. The equation representing the wear X(t) is commonly expressed as follows [16]:

$$dX(t) = \mu\, dt + \sigma\, dW(t) \quad (1)$$

Where μ is the drift coefficient, representing the average wear rate, σ is the intensity of the stochastic variability, and W(t) is the standard Wiener process. The development of this equation allows modeling the accumulated wear over time [16]:

$$X(t) = X(0) + \mu(t) + \sigma W(t) \quad (2)$$

This model is widely used to represent the physical degradation of mechanical components, accounting for both the average failure trend and the random variations that can accelerate or delay the process.

The pure Wiener process describes degradation as an evolution of a purely random characteristic, devoid of any systematic trend. In this model, the wear is represented by the following equation [16]:

$$X(t) = X(0) + \sigma W(t) \quad (3)$$

In addition to stochastic models, to model the degradation of the peristaltic pump more realistically, it is necessary to consider deterministic effects associated with pressure loss and random noise. Zhai and colleagues (2024) [17] represent the pressure loss by a quadratic function of time, which expresses the continuously increasing wear related to prolonged operation, as shown below:

$$P(t) = \alpha t2 \quad (4)$$

For the simulation of the peristaltic pump, parameters were selected based on real data from interviews with a perfusionist and the client who

requested the project, ensuring greater practical adherence to the peristaltic pump's operating conditions.

The pump flow rate under normal operating conditions is 600 mL/min, and this value was fixed in the developed model. In comparison, the equipment failure threshold was set at 480 ml/min, equivalent to 80% of the initial flow rate, which marks the point at which the equipment's performance is considered compromised. The time step was defined as 1 minute, a time resolution suitable for tracking the degradation evolution over the maximum simulated duration of 500 hours (30,000 minutes).

The intensity of the stochastic noise was simulated at three levels: 0.05, 0.3, and 0.8. This variation aimed to represent different operational magnitudes and mechanical imperfections inherent to the process. Table 1 presents the simulation parameters.

Table 1. Simulation parameters for peristaltic pump degradation modeling.

Parameter	Value(s)
Initial Flow ($q0$)	600 mL/min
Failure Threshold (L)	480 mL/min (80% of $q0$)
Time step (dt)	1 minute
Maximum time	500 hours
Noise intensity (σ)	0.05; 0.3; 0.8

The computational simulation was implemented in MATLAB to model the degradation of the peristaltic pump using two distinct stochastic models: Brownian Motion with Drift and the pure Wiener Process. For each model, multiple individual degradation trajectories over time were generated, incorporating stochastic noise and deterministic components. The simulation progressed iteratively until the pump flow reached the established failure threshold or the maximum operating time was reached. During the process, the time-to-failure (TTF) was recorded for each simulation, enabling quantitative analysis of the useful life and comparison of the two models under different variability conditions.

Results

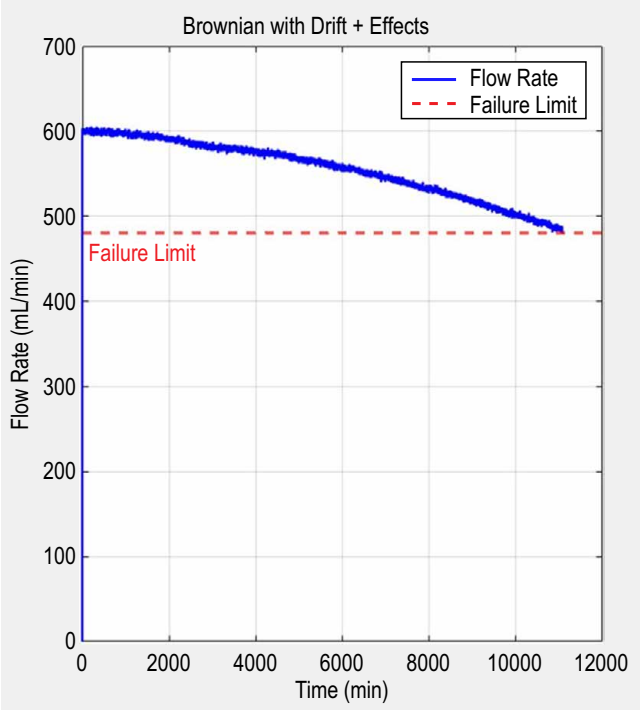
This section presents the results of simulations evaluating the time-to-failure (TTF) of a peristaltic pump used in autologous blood transfusion equipment, accounting for different levels of uncertainty in the degradation process. Two stochastic models were analyzed: Brownian Motion with Drift and the pure Wiener Process. The models were applied to three distinct scenarios of stochastic variability (σ = 0.05, 0.3, and 0.8). The use of these models is relevant for medical applications in which the continuous and safe operation of the pump is highly critical for the integrity of the transfusion procedure and the patient, enabling the anticipation of interventions and reducing the risk of unexpected failures.

In the scenario with σ = 0.05, characterized by low variability, the estimated TTF was 11,070.00 minutes (184.50 h) for the Brownian Motion with Drift model and 15,174.00 minutes (252.45 h) for the pure Wiener Process. At this level of uncertainty, it is observed that the pure Wiener model yielded a time-to-failure greater than that obtained with the Brownian Motion with Drift. Figure 1 presents the simulation results for σ = 0.05.

In the scenario with σ = 0.3, representing moderate process variability, the TTF was 8,786.00 minutes (146.43 h) for the Brownian Motion with Drift model and 12,744.00 minutes (212.40 h) for the Wiener process. As in the previous scenario, the Wiener process showed higher values compared to the Brownian Motion with Drift. Figure 2 presents the simulation results for σ = 0.3.

In the high-variability scenario, modeled with σ = 0.8, the estimated TTF was 6,842.00 minutes (114.03 h) for the Brownian Motion with Drift model and 8,002.00 minutes (133.37 h) for the Wiener process. In this case, the TTF difference between the two models decreased. Figure 3 presents the simulation for the σ = 0.8 scenario.

Figure 1. Comparison between the two stochastic models for σ = 0,05.



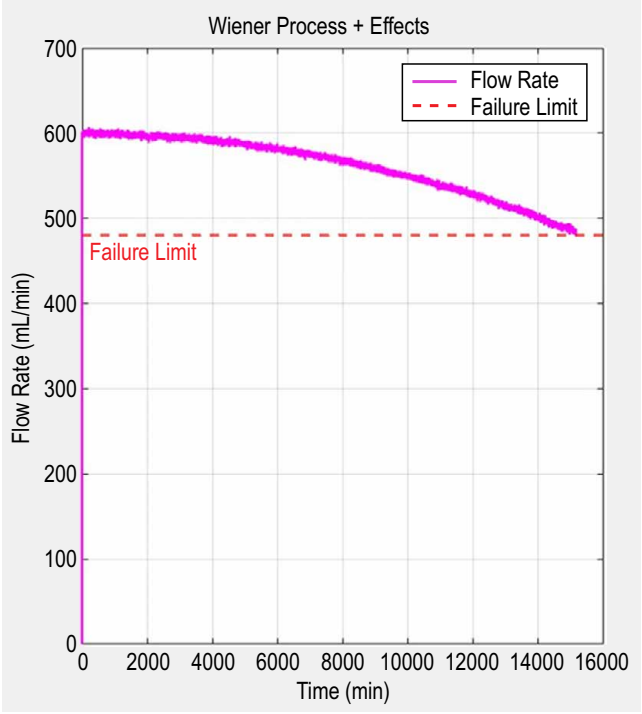
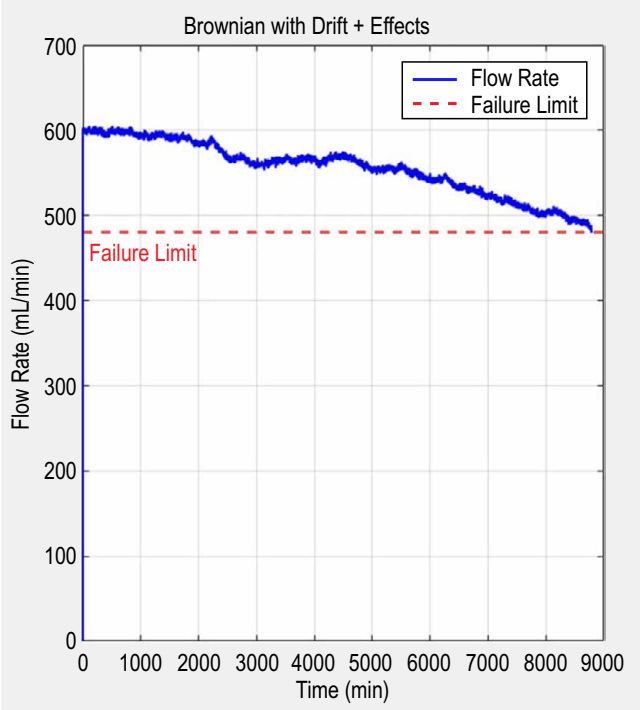


Figure 2. Comparison between the two stochastic models for σ = 0,3.



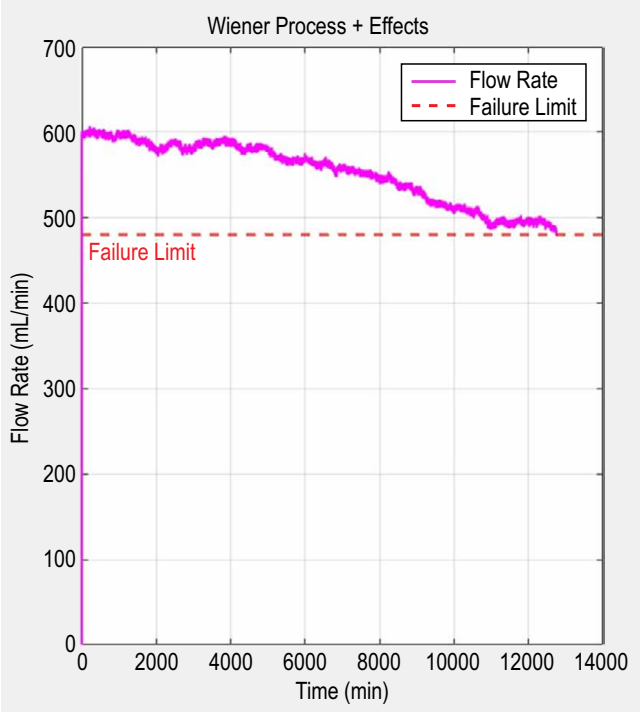
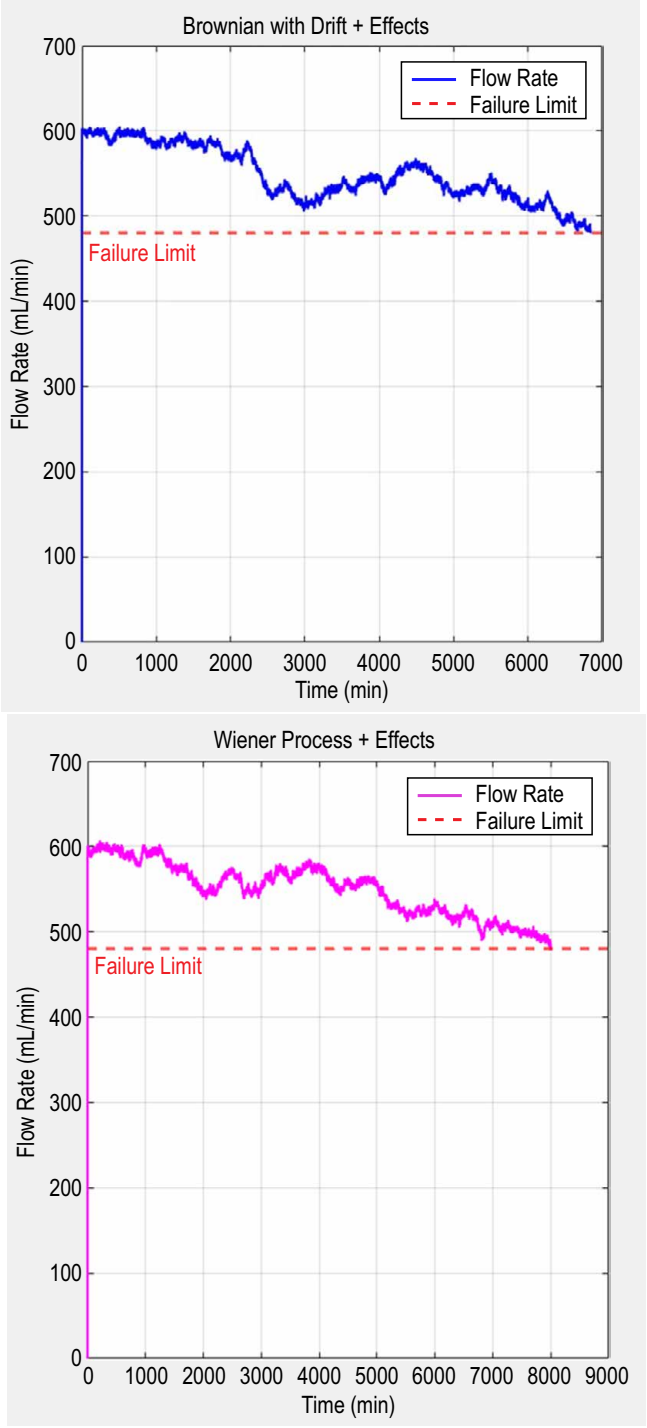


Figure 3. Comparison between the two stochastic models for σ = 0,8.



Discussion

The comparative analysis between the stochastic models of Brownian Motion with Drift and the pure Wiener Process reveals a consistent pattern: across all simulated scenarios, the Wiener Process exhibited higher time-to-failure (TTF) values than the Brownian Motion with Drift model. This difference is more pronounced in low- and moderate-variability scenarios (σ = 0.05 and 0.3) and decreases as process variability increases (σ = 0.8).

The study was conducted to assess the degradation of a peristaltic pump used in a biomedical device, where failure is defined as a reduction in flow rate below a critical threshold required for the safe and effective operation of the system. In this context, understanding the influence of the chosen stochastic model is crucial for accurately estimating the component's lifetime and for planning predictive maintenance actions.

The intrinsic characteristics of each model can explain the observed behavior. In Brownian Motion with Drift, the deterministic term (drift) tends to guide the degradation trajectory toward the failure threshold more consistently, accelerating the average wear rate. In contrast, in the pure Wiener Process, evolution is governed solely by the stochastic term, leading to larger cant oscillations around the mandalich in some c, delaying the attainment of the failure threshold.

In the high variability scenario (σ = 0.8), the TTF difference between the models is considerably reduced. This occurs because increasing the σ parameter amplifies the random effect in both models, making the drift's influence relatively less dominant and bringing the simulated trajectories closer together. In this regime, the impact of random fluctuations prevails over the deterministic component, leading to more irregular, less predictable degradation trajectories.

From a practical perspective, these results indicate that for peristaltic pumps in biomedical applications, the choice of stochastic model can significantly affect lifetime predictions, particularly in processes with low or moderate

variability. Under high-variability conditions, the influence of the chosen model decreases, though it may still be relevant depending on the system's reliability requirements.

Conclusion

The comparative study between Brownian Motion with Drift and the pure Wiener Process, applied to the degradation of a peristaltic pump used in a biomedical device, demonstrated that the choice of stochastic model directly affects the estimation of time-to-failure (TTF). In all scenarios analyzed, the Wiener Process yielded higher TTF values, with the difference more pronounced under low and moderate variability conditions and less pronounced in high-variability scenarios.

The findings suggest that, for biomedical applications where reliability and operational safety are critical, selecting an appropriate degradation model is essential for accurate lifetime predictions and effective predictive maintenance planning. Furthermore, the influence of the chosen model is more relevant in processes with lower variability. In contrast, in highly variable environments, the random component tends to dominate, reducing the differences between the approaches.

As a recommendation for future work, it is suggested to explore hybrid systems that combine stochastic degradation models with statistical monitoring techniques, such as control charts, to enhance early fault-detection accuracy and improve the robustness of lifetime estimation in real operating conditions.

References

1. Conceição MJ. Transfusão sanguínea em crianças e os métodos para evitá-la: uma reavaliação. Rev Bras Anestesiol. 2004;54(2):276-82. Disponível em: https://www.scielo.br/j/rba/a/YXYJ9fR84HSQ5SsnTZFFBgc/.
2. Mello MAA. Avaliação da recuperação de sangue intra e pós-operatória em pacientes submetidos à cirurgia cardíaca com circulação extracorpórea [dissertação]. Campo Grande: Universidade Federal de Mato Grosso do Sul; 2024.
3. Santos AR, Neilson MLH. Bomba peristáltica de duto flexível: reprojeto e melhorias [trabalho de conclusão de curso]. São Paulo: Universidade de São Paulo; 2008.
4. Silva MS, et al. Reliability analysis of hospital infusion pumps: a case study. Biomed Eng Online. 2025;24:55. Disponível em: https://link.springer.com/article/10.1186/s12938-025-01389-2.
5. Zhao Y, et al. Condition-based maintenance for a multi-component system subject to heterogeneous failure dependences. Reliab Eng Syst Saf. 2023;239. Disponível em: https://www.sciencedirect.com/science/article/pii/S0951832023003976.
6. Kardec A, Nascif J. Manutenção: função estratégica. 3. ed. Rio de Janeiro: Qualitymark; 2009.
7. Zamzam AH, Hasikin K, Wahab AKA. Integrated failure analysis using machine learning predictive system for smart management of medical equipment maintenance. Eng Appl Artif Intell. 2023;125. Disponível em: https://www.sciencedirect.com/science/article/pii/S0952197623008990.
8. Park C, Padgett WJ. Stochastic degradation models with several accelerating variables. IEEE Trans Reliab. 2006;55(2):379-90. doi:10.1109/TR.2006.874937.
9. Cai Y, Teunter RH, de Jonge B. A data-driven approach for condition-based maintenance optimization. Eur J Oper Res. 2023;311:730-8. doi:10.1016/j.ejor.2023.05.002.
10. Marotta RD. Modelagem da degradação da superestrutura ferroviária e otimização na alocação de recursos para manutenção [trabalho de conclusão de curso]. Juiz de Fora: Universidade Federal de Juiz de Fora; 2016.
11. Zhang X, et al. Multiple-failure mode division and condition-based maintenance decision making for systems with multi-indicator performance degradation. Comput Ind Eng. 2024;191:110118. Disponível em: https://www.sciencedirect.com/science/article/pii/S0360835224002390.
12. Kadloor S, Adve RS, Eckford AW. Molecular communication using Brownian motion with drift. IEEE Trans Nanobioscience. 2012;11(2):89-99.
13. Zhang Z, et al. Degradation data analysis and remaining useful life estimation: a review on Wiener-process-based methods. Eur J Oper Res. 2018;271(3):775-96.
14. Arias E, Morett G. Confecção de um modelo mecânico análogo para o estudo do movimento browniano e da difusão molecular. Rev Bras Ens Fis. 2023;45:e20230008.
15. Oliveira SC. Modelagem baseada em equações diferenciais estocásticas não-lineares para dinâmica de preços [tese]. Belo Horizonte: CEFET-MG; 2023.
16. Whitmore GA, Schenkelberg F. Modelling accelerated degradation data using Wiener diffusion with a time scale transformation. Lifetime Data Anal. 1997;3(1):27-45.
17. Zhai Q, Li Y, Chen P. Modeling product degradation with heterogeneity: a general random-effects Wiener process approach. IISE Trans. 2024:1-14.

Comparison of Yeast Cell Viability Assessment Techniques Post-Fermentation in *Agave sisalana* Juice

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This study compares different methods for assessing yeast cell viability in *Agave sisalana* juice fermentation, focusing on first-generation ethanol production. Methylene blue staining, CFU counting, and resazurin assays were employed to evaluate cell viability. The results indicated a significant decrease in CFU of yeasts cultivated in *Agave* juice compared to the standard YPD medium. Methylene blue staining did not show a clear difference in viability between the two media. However, resazurin assays revealed a 90% reduction in viability at the 10-3 dilution. The study highlights the interference of *Agave* juice particles, color, and other compounds in the traditional viability assays. Despite these challenges, new methods demonstrated potential for rapid and accurate determination of yeast viability, offering a promising approach for optimizing biotechnological processes in *Agave* juice fermentation. Further research is needed to develop a customized, efficient, and industrially applicable protocol for cell viability assessment in *Agave* juice.

Keywords: *Agave sisalana*. Yeast Viability. Fermentation. Biofuels.

The determination of yeast cell viability is a critical step in monitoring and controlling alcoholic fermentation, particularly in industrial processes for bioethanol production. Accurate assessment of the physiological state of yeast cells directly impacts the efficiency of fermentation, alcohol yield, and the need for operational interventions such as the replacement of viable strains [1].

Viability studies are fundamental because they allow for the early diagnosis of physiological alterations that compromise fermentative performance, including membrane integrity loss, metabolic decline, and cell death. Through these analyses, it is possible to determine the proportion of live and dead cells, the degree of cellular stress, reproductive capacity, and the metabolic vitality of the yeast biomass, providing essential data for real-time decision-making [1,2].

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Several factors, such as bacterial contamination, temperature fluctuations, improper nutrient dosing, and unfavorable physicochemical conditions, negatively affect yeast viability throughout the production cycle, as reported in Brazilian industrial ethanol plants using sugarcane juice [3].

In the context of ethanol production from *Agave sisalana* juice, a promising biomass in Brazil's semiarid region, assessing yeast cell viability becomes even more strategic due to the substrate's distinct chemical composition and the scarcity of studies on its fermentative behavior. Selecting an appropriate analytical method is therefore essential to ensure accurate evaluation of both cell population dynamics and metabolic conditions during bioconversion.

This study aims to compare different techniques for assessing yeast cell viability used in the fermentation of *Agave sisalana* juice, focusing on the production of first-generation (1G) ethanol. The methods investigated include methylene blue staining, colony-forming unit (CFU) counting, and spectrophotometry, with emphasis on their accuracy, sensitivity, and applicability in this biotechnological context.

Materials and Methods

To assess yeast cell viability, two cultivation conditions were applied. The inoculation in YPD broth (Yeast Extract, Peptone, and Dextrose) and the inoculation in *Agave* blend broth (1:1 mixture of *Agave pinha* juice and *Agave sisalana* leaf juice) (Figure 1).

The inoculation in YPD aimed to observe yeast growth in an ideal medium, which was used as a control. A second control was also used, consisting only of *Agave* blend broth (1:1 mixture of *Agave pinha* juice and *Agave sisalana* leaf juice) without the yeast addition, to measure the interference of the "color" factor of the broth in the analyses.

The experiment was conducted by inoculating the commercial yeast CAT-1 (*Saccharomyces cerevisiae*) in tubes containing 5 mL of YPD or *Agave* broth, at a 10% (w/v) yeast proportion, and incubating them in a thermostatic chamber at 32ºC without agitation for a period of 4 hours.

After this period, a 1 mL aliquot was taken from each tube under aseptic conditions and centrifuged at 4000 rpm for 5 minutes. After centrifugation, the supernatant was discarded, and 1 mL of sterile saline (0.85%) was added to the pellet.

The material was resuspended and subsequently diluted in sterile saline (0.85%) to a dilution of 10-6. Aliquots of 100 µL from the 10-2 and 10-6 dilutions were inoculated onto Petri dishes containing BDA medium (Potato Dextrose Agar), using a Drigalski loop and the "spread plate" technique. The seeded plates were incubated in a thermostatic chamber for 24 hours at 32ºC. Afterward, colony-forming units (CFU) were counted.

These same dilutions were also analyzed using the methylene blue and resazurin staining methods. For methylene blue staining, aliquots from the 10-2 and 10-6 dilutions were treated with 0.1% methylene blue at a 1:10 sample ratio. After 5 minutes, a drop of this mixture was placed on a Neubauer chamber, and counting was performed under a microscope. Cell viability was calculated using the following Equation 1.

$$Cell\,s/m\,L = \left(\frac{N}{4}\right) x10^4 xD \qquad (1)$$

Where:

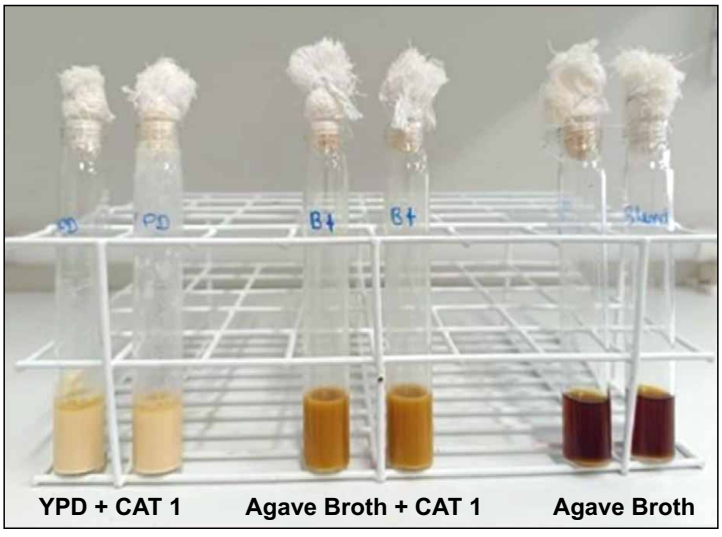
N = total number of viable cells counted in the four large quadrants at the edges.

10^4 = chamber factor (each large quadrant has 10^{-4} mL).

D = dilution inverse.

The resazurin staining was evaluated by scanning the dilutions from 10^{-1} to 10^{-6}, with

Figure 1. Experiment with YPD and *Agave* broth using the commercial yeast CAT-1.



undiluted samples used as a reference for comparison. A 200 µL aliquot from each dilution was placed in the wells of a 96-well microplate. A 20 µL aliquot of resazurin was added to the samples. This mixture was incubated at 32ºC for approximately 2 hours. After incubation, the plate was read for absorbance in a spectrophotometer at 570 and 600 nm.

For assay control, aliquots of the resuspended solution in saline and undiluted solution were added, in addition to wells containing only saline and saline + resazurin. The distribution of the samples is as illustrated in Figure 2. All samples were performed in duplicates.

Results

Viability Assay Using Methylene Blue

Both methylene blue and resazurin are redox dyes that can cross cell membranes and participate in redox reactions within cells. Therefore, intact cells can metabolize these dyes and exhibit different coloration when observed under a microscope.

The difference between viable and non-viable cells is determined by the presence or absence of the dyes inside the cells. The analysis of viable cells using methylene blue staining in a Neubauer chamber showed the results presented in Table 1.

The differentiation was because viable cells appear transparent, while non-viable cells turn blue due to the retention of methylene blue inside (Figure 3).

Viability Count from Growth in BDA Medium

The colony-forming unit (CFU) count in plates containing BDA medium was performed after 24 hours from inoculation. The results are presented in Table 1.

Viability Count Using Resazurin

The cellular viability evaluation for the resazurin assay showed that, at the 10-1 dilution, *Agave* broth exhibited maximum viability (Figure 4). At the 10-2 dilution, no significant reduction was observed, with similar values between the media (47.6% for YPD and 47.4% for *Agave* broth). From the 10-3 dilution onwards, viability was significantly reduced, with values of 3.3% for YPD and 0.5% for *Agave* broth. No activity indicative of cellular viability was detected in subsequent dilutions for any of the treatments.

Figure 2. Microplate containing the samples (A) and schematic distribution of the samples in the microplate (B).

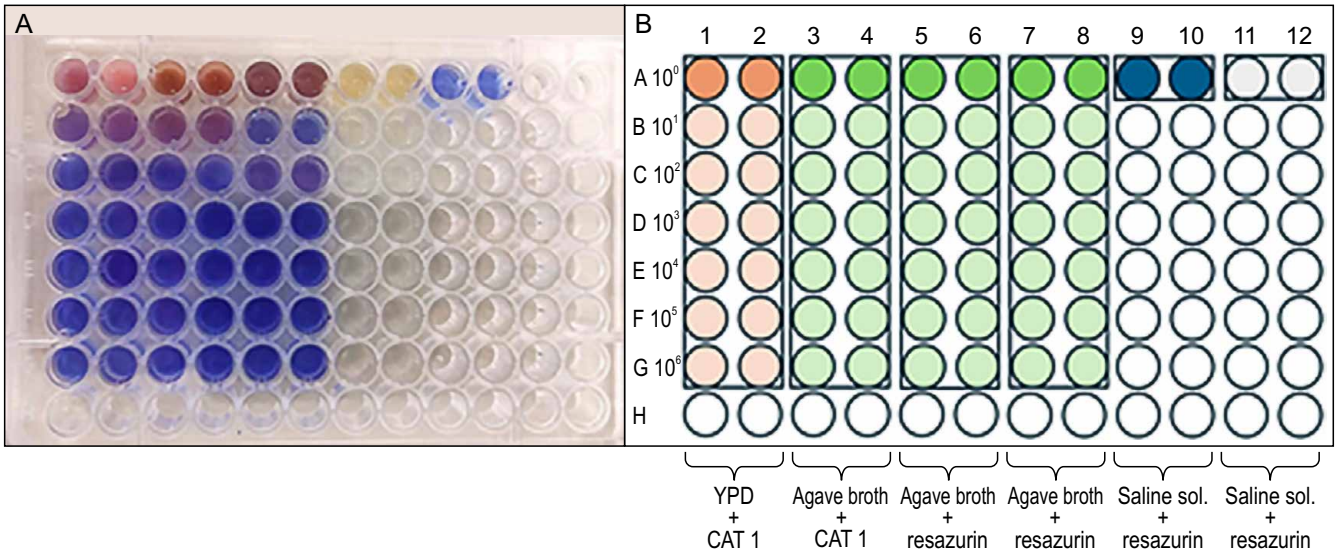


Table 1. Results of viability counts using methylene blue staining and CFU/mL in BDA culture medium.

Sample Type	Dilution Factor	Methylene Blue Staining Viable Cells/mL	Seeded on BDA Medium CFU/mL
YPD + CAT 1	10^{-2}	$1.37x10^{8}$	$>3x10^{5}$
	10^{-6}	$6.25x10^{9}$	$1.27x10^{9}$
Agave broth + CAT 1	10^{-2}	$5.64x10^{8}$	$>3x10^{5}$
	10^{-6}	$5x10^{9}$	$8.3x10^{8}$
Agave broth (control)	10^{-2}	0	0
	10^{-6}	0	0

Figure 3. Methylene blue staining difference between viable and non-viable cells, observed under an optical microscope at 400x magnification.

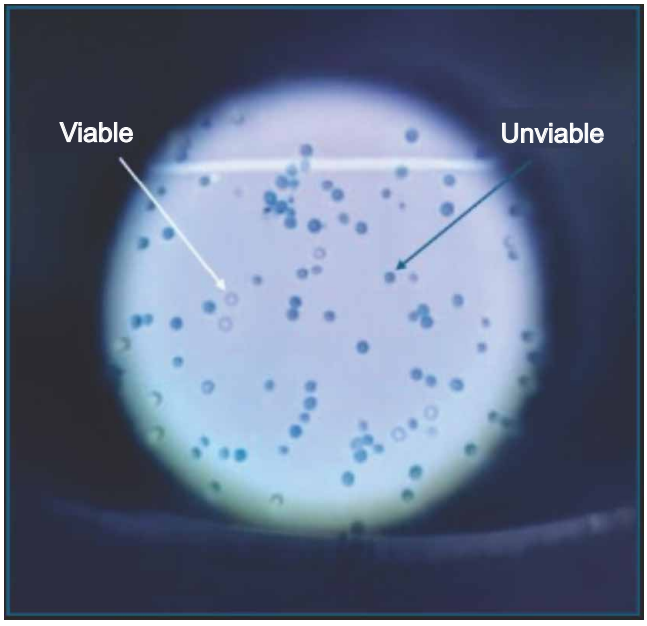
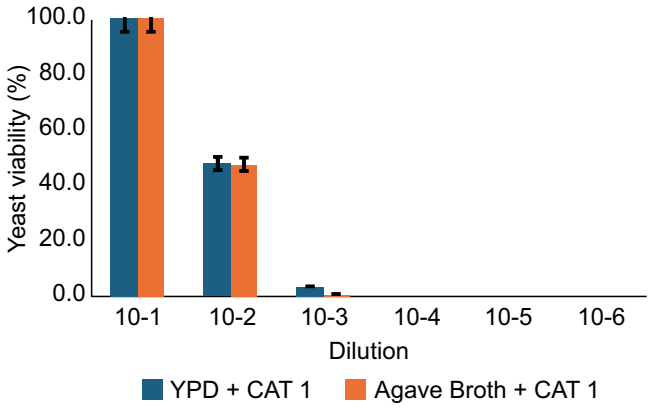


Figure 4. Viability results (%) of yeast cells based on resazurin staining.



Discussion

Some classical methods for determining cell viability may exhibit low efficiency under cellular stress conditions [4,5]. The production of ethanol from *Agave sisalana* juice is unprecedented, and therefore, studies on the behavior of yeasts in this material are virtually non-existent. *Agave* juice may contain components (particles, saponins, organic acids) that could affect the physiological behavior of yeasts, inducing stress in the cells.

It is noteworthy that counting a large number of samples also affects the efficiency of the method [6].

To reliably determine cell viability, CFU counting is the most suitable method [7]; however, it is time-consuming. Table 1 shows a 10x decrease in CFU of yeasts cultivated in *Agave* juice compared to the YPD cultivation medium. However, it was not possible to correlate the decrease in cell viability between the standard medium (YPD) and *Agave* juice using the methylene blue method.

Regarding the application of resazurin, a 90% reduction in cell viability was observed starting at the 10-3 dilution. It is possible that adjustments in incubation time and inoculum [8] could indicate a faster method for better response in cell viability analysis in *Agave* juice.

Cell viability assays commonly use dyes that change color under pH alterations or redox reactions. Many of these determine dehydrogenase activity [9], and the activity of these enzymes can be more accurately expressed depending on the different physiological states of the studied cells.

One hypothesis raised in this study concerns the particles in the juice, which may be an interfering factor in classical viability analyses using dyes. In spectrophotometry, solids artificially increase absorbance due to light scattering, chemically reacting and affecting readings at wavelengths used for dyes such as methylene blue or resazurin [10-12].

Thus, this study compares three different methods for analyzing cell viability, demonstrating that the microorganism and the medium in which it is cultivated determine which method is most appropriate. Moreover, adaptations must always be considered due to the specificities of each fermentation process.

Conclusion

This study concludes that cell viability assays using dyes need to be customized or adapted when applied to fermentations with *Agave* juice. The particles in the medium, the color, and other unidentified compounds affect the analyses, resulting in inconclusive findings. However, this study also highlights the potential of new methods to be customized and quickly identify yeast viability accurately, with results consistent with those obtained from CFU counting. New methods can be evaluated to develop a personalized, efficient, rapid, and industrially applicable protocol for determining yeast cell viability in *Agave* juice.

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References

1. Jacob AB, Campos RT. Estudo sobre a viabilidade celular da levedura no processo de fermentação em uma usina de álcool e açúcar. Environ Sci Technol Innov. 2023;1(2):108-131.
2. Kwolek-Mirek M, Zadrag-Tecza R. Comparison of methods used for assessing the viability and vitality of yeast cells. FEMS Yeast Res. 2014;14(7):1068-1079. Available from: https://doi.org/10.1111/1567-1364.12202
3. Nobre TP, Horii J, Alcarde AR. Viabilidade celular de *Saccharomyces cerevisiae* cultivada em associação com bactérias contaminantes da fermentação alcoólica. Ciênc Tecnol Aliment. 2007;27(1):20-25.
4. Postgate JR. Viability measurements and the survival of microbes under minimum stress. Adv Microb Physiol. 1967;1:1-23. Available from: https://doi.org/10.1016/S0065-2911(08)60248-9
5. Deere D, Shen J, Vesey G, Bell P, Bissinger P, Veal D. Flow cytometry and cell sorting for yeast viability assessment and cell selection. Yeast. 1998;14(2):147-160. Available from: https://doi.org/10.1002/(SICI)1097-0061(19980130)14:2<147:AID-YEA204>3.0.CO;2-L.
6. Matsumoto A. A rapid and simple spectroscopic method for the determination of yeast cell viability using methylene blue. Yeast. 2022;39(1-2):30-36. Available from: https://doi.org/10.1002/yea.3662
7. Wang R, Lorantfy B, Fusco S, Olsson L, Franzén CJ. Analysis of methods for quantifying yeast cell concentration in complex lignocellulosic fermentation processes. Biotechnol Biofuels Bioprod. 2022;15:49. Available from: https://doi.org/10.1186/s13068-022-02118-6
8. Medina ABP, Piñanez JRC, Alvarez MFP, Farias CJ de. Use of 2,3,5-triphenyl tetrazolium chloride for detection of Fusarium semitectum viability in soybean seeds. J Seed Sci. 2024;46:e202446021. Available from: https://doi.org/10.1590/2317-1545v46278215
9. Stockert JC, Horobin RW, Colombo LL, Blázquez-Castro A. Tetrazolium salts and formazan products in cell biology: viability assessment, fluorescence imaging, and labeling perspectives. Acta Histochem. 2018;120(3):159-167. Available from: https://doi.org/10.1016/j.acthis.2018.02.005
10. Harrison P, et al. The influence of sample turbidity on spectrophotometric and fluorometric assays of microbial cell viability. J Microbiol Methods. 2015;119:26-32. Available from: https://doi.org/10.1016/j.mimet.2015.09.004
11. Holder SJ, Holland NB, Duncan R. Particle-induced artifacts in the MTT and LDH viability assays. Appl Sci. 2021;11(10):4410. Available from: https://doi.org/10.3390/app11104410
12. Rampersad SN. Multiple applications of alamar blue as an indicator of metabolic function and cellular health in cell viability bioassays. Sensors. 2012;12(9):12347-12360. Available from: https://doi.org/10.3390/s120912347.

Technical and Economic Feasibility Study of Castor Bean Biorefinery

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This study presents a technical and economic feasibility analysis for the implementation of a biorefinery for the extraction and processing of castor oil (*Ricinus communis* L.) in Bahia, Brazil. Castor oil is an oilseed of great industrial importance, known for its resilience to adverse climatic conditions and its wide range of applications in the chemical, pharmaceutical, cosmetic, and energy sectors, particularly due to the presence of castor oil. Accordingly, this work is based on its potential as a sustainable alternative to fossil sources, the valorization of regional production chains, and the promotion of socioeconomic development in Brazil's semi-arid Northeast. Furthermore, the high added value of castor oil and the potential for full biomass utilization justify investments in well-structured biorefinery projects. Both qualitative and quantitative methods were used to determine the optimal location, with Irecê (Bahia) identified as a strategic site. The hot pressing technology was selected for its high yield and simplicity. Two production capacity scenarios were evaluated: a high-capacity scenario (150 t/day), which demonstrated excellent economic viability (NPV of R$ 148 million, IRR of 38%, and a payback period of 3 years), and a medium-capacity scenario (50 t/day), which yielded negative results (NPV of -R$ 19 million, IRR of 6%). It is concluded that the implementation of a large-scale biorefinery is viable and promising, provided it is supported by strategies to reduce market volatility and optimize operational costs, thereby contributing to the strengthening of the castor production chain and the sustainable development of the region.
Keywords: Castor Bean. Northeast. Oil. Feasibility. Biomass.

The search for renewable and sustainable energy sources has intensified in recent decades, driven by climate change, oil price volatility, and the need to diversify the global energy matrix. In this context, plant biomass stands out as a promising alternative, produced by plants in the form of lignocellulosic material, sugars, starches, and oils. Brazil, favored by natural conditions such as a tropical climate, fertile soils, and abundant water resources, is one of the world's largest producers of biomass. Among all culture energies sources, sugarcane has held a prominent position since the 15th century, contributing significantly to ethanol production and electricity cogeneration from bagasse [1].

Castor bean (*Ricinus communis* L.), although less exploited, is an oilseed with high industrial potential, with applications in the chemical, pharmaceutical, cosmetic, and biofuel sectors due to the extraction of castor oil. Traditionally cultivated by small and medium-sized farmers, it holds social relevance and potential for income generation in rural areas [2]. Historically, Brazil led global production of castor seeds and castor oil, but in recent decades has lost this position to countries such as India and China [3]. Despite its presence in several regions, castor bean cultivation still lacks technological advances, agronomic studies, genetic improvement, and the development of large-scale processing technologies. In addition, a major challenge is the presence of ricin, a highly toxic protein found in the seeds that inhibits protein synthesis in eukaryotic cells. This toxicity limits the use of the residual cake, a by-product of oil extraction, particularly for animal feed due to toxicological risks. Research efforts have been made to develop varieties with lower ricin content and detoxification processes, aiming to expand the safe use of this by-product.

Given this scenario, the present study aims to conduct a Technical and Economic Feasibility Study (TEFS) for the implementation of a biorefinery dedicated to castor bean processing in the state of Bahia, considering the region's agricultural potential

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and the full utilization of biomass. In addition to oil extraction, the study seeks to evaluate the use of the residual cake as a value-added by-product, contributing to the strengthening of the castor bean value chain and the sustainable development of the semi-arid Northeast region of Brazil.

Materials and Methods

To carry out the economic feasibility study for the implementation of a castor bean biorefinery, methodological steps were followed to ensure a comprehensive analysis from market characterization to the definition of production capacity and cost estimation, using literature review, secondary data, and both quantitative and qualitative analyses.

Market Characterization

To characterize the current market, research was conducted using scientific articles, government and institutional databases such as Embrapa and the National Supply Company (Conab), along with a demand projection through 2027 based on data from the Our World in Data platform. The objective was to understand the status of the castor bean value chain in Brazil and globally, as well as to obtain relevant statistical data for the study. It was observed that the Brazilian market shows a slight downward trend in production, although it remains relatively stable.

Technological Route Definition and Plant Location

Subsequently, technological routes for oil extraction and the utilization of castor cake were evaluated. Based on technical and economic criteria, the process selected was hot pressing followed by solvent extraction, due to its high yield and feasibility at the proposed scale. From this definition, a process flow diagram was developed, and the main utility requirements such as thermal and electrical energy and process water were identified.

Following the definition of the production process, it was necessary to identify the most efficient location for establishing the biorefinery. Considering Bahia's relevance in Brazil's castor bean production, three municipalities were selected as potential locations: Luís Eduardo Magalhães, Barreiras, and Irecê. Initially, the The Gravity Center method was applied, based on the geographical distribution of the main castor-producing regions and the consumer centers for its by-products (oil and cake), following the approach used in Oliveira and colleagues [4]. This method enabled the estimation of the optimal logistical location, aiming to streamline product distribution and minimize transportation costs by considering weighted distances.

In addition to the quantitative approach, a qualitative weighting matrix was employed using strategic criteria such as proximity to production areas, logistical infrastructure (roads, railways, and distribution centers), and the availability of resources (water, energy, and labor). This multicriteria assessment allowed for a broader comparison of the alternatives, taking into account not only logistical aspects but also operational and socioeconomic factors.

Mass Balance

For the mass balance stage, it was assumed that the raw material used consists of 100% clean, dehulled castor seeds that is the pretreatment stage (cleaning and dehulling) was carried out beforehand and is not included in the following calculations. The calculations were based on the assumptions presented in Table 1.

Table 1. Base data for mass balance.

Base Data	
Acidity level (%)	2%
Pressing (%)	48%
Oil in Cake	6%
Oil in Centrifuge	97%
Neutralization	0.00199
Water input	10%

An empirical factor (0.00199) was used, based on the stoichiometry of the saponification reaction between free fatty acids (FFA) and sodium hydroxide, to estimate the required amount of base. This value, widely accepted in technical and industrial literature, relates the acidity level of the oil to the processed mass, taking into account the average molar mass of the main fatty acids and the molar ratio of the reaction [5].

Economic Analysis

For the economic analysis, two plant production capacity scenarios were considered: 150 t/day and 50 t/day. The 150 t/day capacity was intentionally overestimated, representing an optimistic large-scale operation scenario aimed at evaluating the maximum economic potential of the process under ideal continuous production conditions. On the other hand, the 50 t/day capacity reflects a more conservative and realistic estimate, compatible with a medium-scale processing unit feasible for regional implementation. This comparison allowed for assessing the sensitivity of economic indicators to project scale and helped define a model better suited to the socioeconomic reality of the region.

Equipment costs were estimated based on 1990 data from Lima [6], updated to 2024 using the Chemical Engineering Plant Cost Index (CEPCI) and converted to Brazilian reais using a nationalization factor (1.2), due to the lack of specific data on individual costs and energy consumption. The annual net revenue was calculated from the estimated production of castor oil and cake, considering average market prices and applying a 30% tax burden. Fixed plant costs were estimated, including investments in ISBL (Inside Battery Limits) and OSBL (Outside Battery Limits), startup investment (10% of fixed investment), and working capital. The sum of these values resulted in the total project investment. The annual operating cost (OPEX) was obtained by summing fixed and variable costs.

Based on these data, the annual cash flow was projected over a 10-year horizon, considering straight-line depreciation of fixed investment, operational costs, tax burden, and estimated revenue. The economic feasibility analysis was conducted through the calculation of the Net Present Value (NPV), using a Minimum Attractive Rate of Return (MARR) of 14.75%, corresponding to the SELIC rate as of May 2025 (Equation 3).

In addition to NPV, the Internal Rate of Return (IRR), breakeven point, payback period, and profitability index (PI) defined as the ratio between the accumulated NPV and the initial investment (Equation 4) were calculated. Finally, a sensitivity analysis was performed to evaluate the effects of variations in selling prices and operational costs on project feasibility.

The following Equations were used for the calculations:

$$I_1 = I_2\left(\frac{C_1}{C_2}\right)^{f} \quad (1)$$

Where *I1* is the cost in 2024, *I2* is the cost 1990; f=0,6; C_1=798,8 ; C_2 =100

$$I_{Brazil} = F * I_{EUA} \quad (2)$$

$$NPV = \sum_{j=0}^{n} \frac{FC_j}{(1+i)^{J}} \quad (3)$$

$$PI = \sum_{j=0}^{n} \frac{FC_j}{(1+i)^{J}} \; / \; FC_0 \quad (4)$$

Results

Market Potential and Location

The analysis of global availability of the raw material castor bean (*Ricinus communis* L.) revealed that the largest producers are mainly located in Brazil, China, and India, the latter responsible for approximately 1.98 million tons in 2023 (Our World in Data). By applying plant location selection methodologies highlighting qualitative weighting and geolocation of production capacity the region near Irecê was identified as the most suitable for establishing the castor oil extraction and processing

unit,due to logistical advantages and the availability of raw material in the area.

Results of Mass Balance

The castor oil extraction process and utilization of the cake were structured in stages integrating thermal, mechanical, and chemical operations to optimize yield and quality, as well as to ensure the safe reuse of the residual cake, based on Kaur R, Bhaskar [7]. Initially, the seeds underwent cooking with saturated steam to facilitate mechanical extraction by hot pressing, which also helps denature the ricin present in the cake. The extracted oil was centrifuged to separate impurities and subsequently subjected to chemical neutralization to remove free fatty acids, thereby improving its stability. To recover residual oil from the cake, solvent extraction with hexane was performed, followed by distillation to separate the solvent from the pure oil. The residual cake underwent thermal and chemical detoxification to neutralize ricin, making it safe for use, and was then dried to reduce moisture content, facilitating storage and transportation, as illustrated in Figure 1.

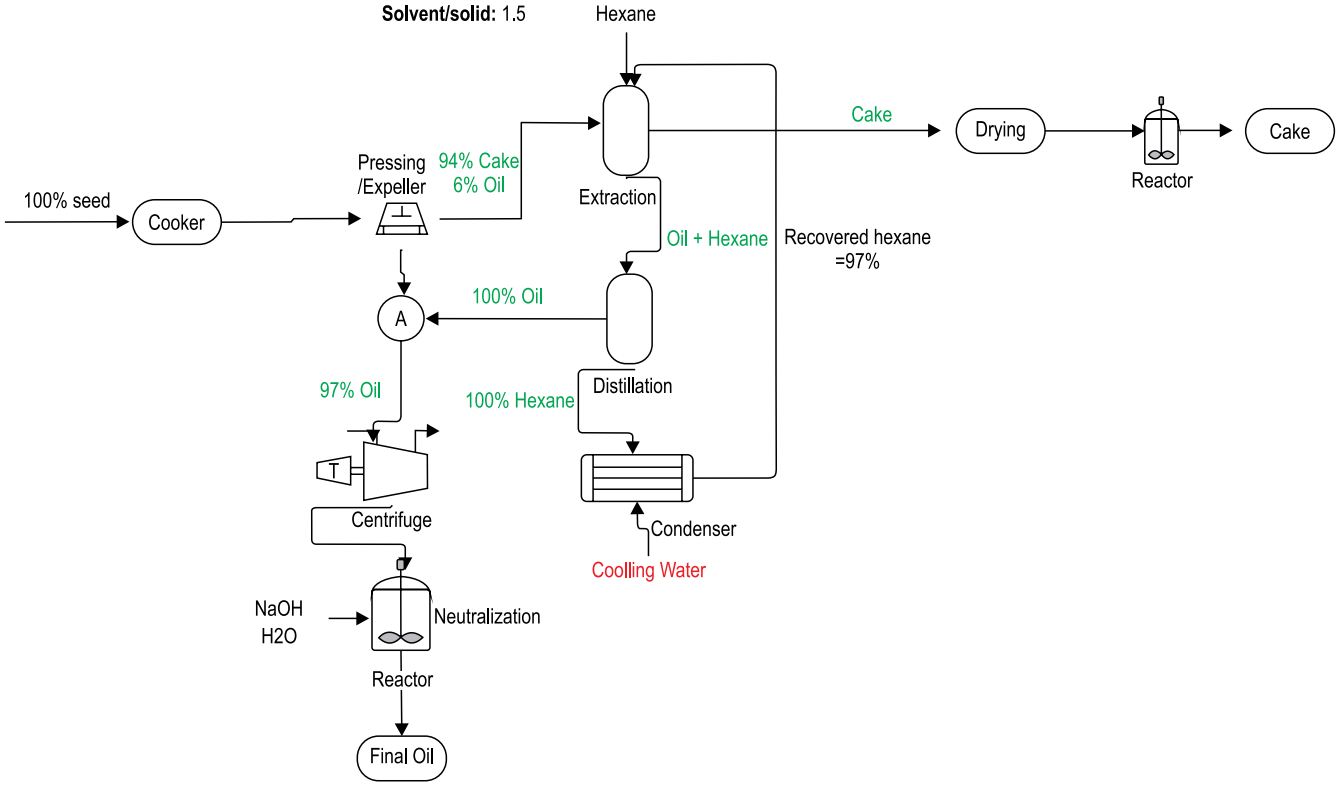
Technical and Economic Feasibility Study

To evaluate the economic feasibility of the project under different production scales, a sensitivity study was conducted considering two operational capacity scenarios for the castor processing plant. Variations in plant capacity implied proportional adjustments in revenue, fixed costs, and variable costs. Elements such as utility consumption (water, steam, electricity) and logistics costs were scaled according to the size of each scenario.

Scenario 1 – Overestimated Plant Capacity

In the first scenario, a plant with a processing capacity of 150 tons per day was considered, exceeding the average reported in the literature. The

Figure 1. Process flowsheet.



estimated annual oil production was approximately 27.2 million kg, assuming 8,000 effective operating hours per year, including downtime for maintenance and other interruptions.

Based on the quantities of oil and cake produced, with prices set at BRL 45.00/kg and BRL 19.40/kg, respectively, the plant's annual net revenue was calculated. After applying a 30% tax rate, the resulting amount was BRL 1,189 million.

For the calculation of fixed investments, direct and indirect labor costs were estimated based on the number of required positions and employees, in addition to construction costs for an estimated area of 1,000 m². Accordingly, the total ISBL costs amounted to BRL 11.44 million, and OSBL costs to BRL 90.61 million, resulting in a total fixed investment of BRL BRL 102.02 million.

Considering the unit prices of castor seeds, solvents, and NaOH, the process variable costs were estimated based on the quantities calculated in the mass balance, totaling BRL 138.87 million, as shown in Table 2.

Table 2. Total variable costs – Scenario 1.

Item	Cost
Castor Seeds	BRL 7,200,000.00
Hexane Solvent	BRL 58,500.00
Sodium Hydroxide (NaOH)	BRL 7,477.29
Utilities	BRL 118,943,892.77
Supplies	BRL 37,573.93
Transportation	BRL 12,624,744.40
Total	BRL 138,872,188.38

The OPEX value was obtained by summing the fixed and variable costs, resulting in BRL BRL 240.84 million.

Scenario 2 – Plant Capacity Based on the Average

As in the first scenario, the same calculations were performed; however, for a plant capacity of 50 tons per day, which reflects typical medium-scale industrial plants. This capacity resulted in an annual production of approximately 9,074,536.80 kg of castor oil and 8,146,666.67 kg of castor cake. Due to this change, there was a variation in revenue, variable costs, and logistics costs, resulting in an annual net revenue of BRL 396.48 million. Regarding the fixed costs for the plant operating at average capacity, only logistics costs were altered, decreasing significantly since they correspond to 7.6% of the revenue value, according to the assumption made. The total ISBL costs amounted to BRL 11.44 million and OSBL costs to BRL 30.35 million, demonstrating a total fixed investment of BRL 41.79 million, a considerably lower amount than in Scenario 1.

With the change in plant capacity, variable costs were the most impacted, as shown in Table 3.

Table 3. Total variable costs – Scenario 2.

Item	Cost
Castor Seeds	BRL 2,400,000.00
Hexane Solvent	BRL 19,500.00
Sodium Hydroxide (NaOH)	BRL 2,492.43
Utilities	BRL 39,647,964.26
Supplies	BRL 37,573.93
Transportation	4,210,753.06
Total	BRL 46,318,283.68

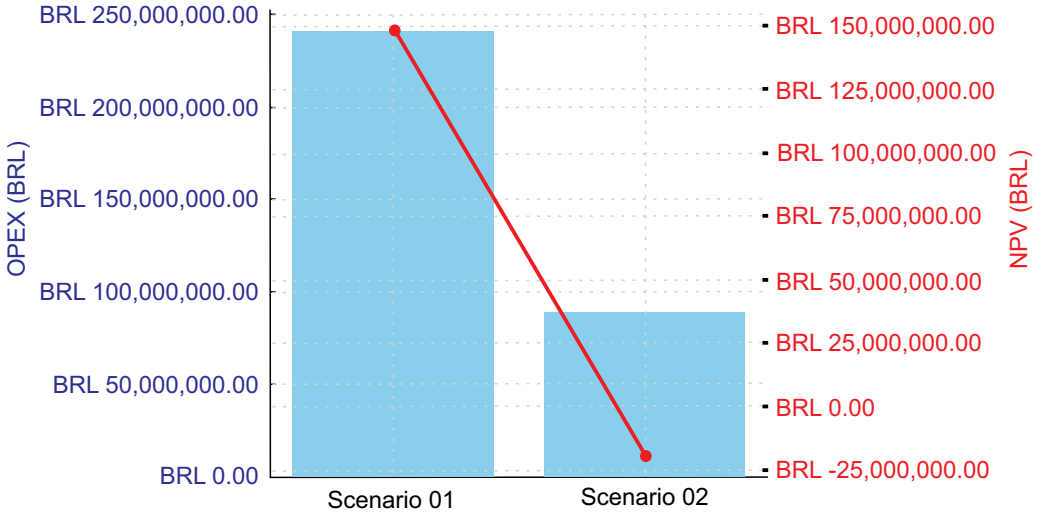
The OPEX value was obtained by summing the fixed and variable costs, resulting in BRL 88.11 million.

Sensitivity Analysis

For this analysis, a significant difference in operational costs (OPEX) is initially observed, which directly influences the Net Present Value (NPV), as illustrated in Graphic 1.

Although it presents higher operational costs, the overestimated scenario achieved a positive Net Present Value (NPV) of BRL 148 million, demonstrating economic feasibility. In contrast, the medium-scale plant, despite its lower cost, showed a negative NPV of approximately BRL 19 million.

Graphic 1. Comparison of NPV and OPEX.



Regarding the payback period, it was observed that the plant in Scenario 1 achieves return in 3 years, while the medium-scale plant has a payback period of approximately 8 years.

The results indicate that the overestimated scenario (Scenario 1) is significantly more advantageous from a financial perspective. It presents a shorter payback time and greater cash generation over time, accumulating substantial profit. In this scenario, the Internal Rate of Return (IRR) was 38%, a value substantially higher than the adopted Minimum Attractive Rate of Return (MARR) of 14.75% (SELIC), highlighting the high economic viability of the project. This means that, beyond recovering the initial investment, the project generates an attractive profit margin, justifying the higher capital outlay.

On the other hand, the medium-scale scenario (Scenario 2) presented an IRR of only 6%, well below the MARR. Although the investment may be recovered over the years, the financial risk is higher and the profit potential is limited, making the project less competitive.

Additionally, the cash flow analysis reveals that both scenarios operate profitably from the start of production. Scenario 2 shows that sales revenue exceeds total costs (fixed and variable) across the entire operating range (0% to 100% of capacity), indicating that there is no apparent breakeven point, as the operation remains profitable even at low utilization levels.

The Profitability Index (PI) analysis further reinforces the superiority of the overestimated scenario, which achieved a positive value of 1.01, indicating that for every real in revenue, BRL 0.01 in profit is generated. In contrast, the medium-scale scenario presented a negative PI of -0.32, indicating an operational loss.

Despite its overall inferior performance, the second scenario demonstrated that reducing operational costs, especially variable costs, has a positive impact on the NPV, highlighting the importance of efficient management of inputs such as raw materials, energy, and labor.

Conclusion

The use of castor beans for oil extraction represents a strategic opportunity, given the high value of the product and its broad industrial applications. However, price volatility introduces uncertainty into the supply chain, making the proper sizing of processing plants essential for the project's viability.

Based on the results, it is concluded that the overestimated scenario, despite its higher costs and deviation from current market conditions, shows superior economic performance. The

positive NPV, high IRR, quick payback period, and overall profitability indicate that the higher initial investment is compensated by better operational results. In contrast, the medium-scale plant is financially unfeasible, with a slow return, IRR below the MARR, and operating at a loss.

Given the sector's instability, it is recommended to conduct broader sensitivity analyses, varying parameters such as prices, operational costs, production capacity, and discount rates. This approach will help assess the robustness of the project and ensure the economic sustainability of the castor oil production chain in the face of market uncertainties.

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References

1. Pinho M, Toneto Jr R, organizadores. Economia de baixo carbono: impactos de novos marcos regulatórios e tecnologias sobre a economia brasileira. Ribeirão Preto: FUNPEC Editora; 2015. p. 394.
2. Parrella NNL de, Carvalho MLM de, Parrella RAC da C, Resende JCF de, Reis JBR da S. Caracterização fisiológica e sanitária de sementes de mamona utilizadas na safra 2006 no estado de Minas Gerais. Sete Lagoas: Embrapa Milho e Sorgo; 2009. 23 p.
3. Sausen TL. Respostas fisiológicas de *Ricinus communis* à redução na disponibilidade de água no solo [dissertação]. Porto Alegre: Faculdade de Agronomia, Universidade Federal do Rio Grande do Sul; 2007. 105 f.
4. Oliveira BF, Neto JO, Silva JK, Santoro PPC. Uso do centro de gravidade para localizar a base operacional da TPG do Brasil. In: Anais do XIII Simpósio de Excelência em Gestão e Tecnologia – SEGeT; 2015 Oct 28–30; Resende, Brazil. Resende: AEDB; 2015. Available from: https://www.aedb.br/seget/arquivos/artigos15/24722311.pdf
5. American Oil Chemists' Society. Official methods and recommended practices of the AOCS. 6th ed. Urbana: AOCS Press; 2009.
6. Lima PF. Análise da viabilidade econômica da produção de óleo de mamona de primeira geração no Rio Grande do Sul.Porto Alegre: Universidade Federal do Rio Grande do Sul, Programa de Pós-Graduação em Agronegócios; 2002. Available from: http://hdl.handle.net/10183/5294.
7. Kaur R, Bhaskar T. Potential of castor plant (*Ricinus communis*) for production of biofuels, chemicals, and value-added products. In: Moser BR, editor. Handbook of Biofuels Production. 2nd ed. Cambridge: Woodhead Publishing; 2020. p. 211–223. doi:10.1016/B9780128182284000113

Investigation of The Use of PEG as a Compatibilizer in Nanocellulose Reinforced PLA Composites

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Poly(lactic acid) (PLA) is a widely used biodegradable polymer due to its renewable origin and favorable environmental properties. However, its low ductility and impact resistance limit its use in more demanding applications. In this context, this study investigated the formulation of PLA composites with a masterbatch containing natural trichomes, cellulose nanofibrils (NFC), and polyethylene glycol (PEG), with the aim of improving the interfacial compatibility and mechanical properties of the material. The literature shows that NFC can reinforce the polymer matrix, but its dispersion is hampered by the difference in polarity with PLA, making it necessary to use compatibilizers such as PEG. The experimental results indicated that formulations with balanced NFC and PEG contents showed significant improvements in mechanical strength and deformation at break, especially those that employed the PEG masterbatch (MB) strategy. The proposed approach proved to be effective and sustainable, expanding the potential application of PLA in sectors that demand higher performance, such as technical packaging, biodegradable films, and structural components from renewable sources.
Keywords: PLA. Cellulose Nanofibrils. PEG. Compatibilization. Biocomposites.

Growing environmental concern over the accumulation of non-biodegradable plastic waste has led to the development of sustainable alternatives, such as polymers of renewable origin. Among these, poly(lactic acid) (PLA) stands out because it is biodegradable, biocompatible and comes from natural sources such as corn starch or sugar cane. However, PLA has limited mechanical properties, such as low impact resistance and reduced ductility, which restricts its application in more demanding sectors [1].

In order to overcome these limitations, the incorporation of natural trichome reinforcements, such as cellulose nanofibrils (NFC), has proved to be a promising alternative. Due to its high stiffness, high aspect ratio and abundance of hydroxyl groups, NFC acts as a structural reinforcement and can significantly improve the modulus of elasticity and tensile strength of composites [2,3]. However, the presence of these hydroxyl groups also gives NFC its hydrophilic character, which makes it difficult to disperse it homogeneously in hydrophobic matrices such as PLA [4].

In this scenario, the use of compatibilizing additives such as poly(ethylene glycol) (PEG) has become an effective strategy. PEG can interact with the surface of the NFC through hydrogen bonds, promoting surface modification of the nanofiber and facilitating its incorporation into the polymer matrix. In addition, PEG acts as a plasticizer, reducing the crystallinity of PLA and increasing its ductility [5].

The study by Cailloux and colleagues (2019) [6] demonstrated that levels of up to 20% PEG in wet suspension can be used in NFC pretreatment, favoring its individualization. This procedure improves nanofibril dispersion and contributes to greater compatibility with the PLA matrix, optimizing the composite's performance. The study carried out by, Clarkson and colleagues (2020) [7] used lower concentrations, such as 5% by weight, also with satisfactory results. This data indicates a wide range of possible PEG contents to be investigated, with direct impact on the structural and functional properties of the composite.

Therefore, this work proposes a PLA composite formulation containing a masterbatch with

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natural trichomes, NFC, and PEG, with the aim of evaluating the efficiency of PEG as a compatibilizing agent and plasticizer, promoting better nanofiller dispersion and improving mechanical performance. The choice of this composition is based on several pieces of evidence in the literature [2,8,9], which point to the synergistic potential between natural reinforcements and plasticizers in biodegradable matrices.

Materials and Methods

The composites were prepared by melt mixing PLA (Natureworks 3D850), masterbatch (MB: PLA/5wt% trichome), nanofibrils (manufactured by TRL9) and PEG (PEG-600) (Table 1 and 2), using co-rotating twin-screw extruder (DR.16.40.AX from AX Plásticos), speed 135 rpm, temperature range 150 to 190. Followed by filament production using Filmaq 3D single-screw extruder, speed 32 rpm, temperature 190ºC. And 3D printing (Prusa Research MK3S+ 3D) to produce tensile test specimens.

Table 1. Formulations without added PEG.

Formulation	PLA	Masterbatch	NFC
F1	100.0%	–	–
F2	99.5%	0.5%	–
F3	99.5%	–	0.5%
F4	99.0%	0.5%	0.5%
F5	98.5%	0.5%	1.0%
F6	97.5%	0.5%	2.0%

Table 2. Formulations with added PEG.

Formulation	PLA	Masterbatch	NFC	PEG
F1	97.0%	–	–	3.0%
F2	96.5%	0.5%	–	3.0%
F3	96.5%	–	0.5%	3.0%
F4	96.0%	0.5%	0.5%	3.0%
F5	95.5%	0.5%	1.0%	3.0%
F6	94.5%	0.5%	2.0%	3.0%

The formulation specimens were prepared in accordance with ASTM D638, type IV and were tested on an EMIC model DL200MF universal testing machine with a 2 kN load cell, speed test 5 mm/min, 5 replicates for each formulation. The properties analyzed were tension at maximum force (MPa), specific deformation at break (%) and modulus of elasticity (MPa). Morphological analyses were performed using digital optical microscopy (Nova Digital) to evaluate the fracture surface of the fractured tensile specimens.

Data from the tensile tests were analyzed by ANOVA, followed by the Tukey test ($p<0.05$) to compare means, using Statistica 7.0 software.

Results and Discussion

A Prusa Research MK3S+ 3D printer was used to fabricate the specimens (Figure 2). This method ensured precise control of the sample geometry, enabling consistent and reproducible preparation for mechanical characterization. The printing process also demonstrated good processability of the formulations, especially those containing PEG, which contributed to smoother extrusion and an improved surface finish.

Figures 3, 4, and 5 display the results of the tensile tests conducted on the different formulations, representing, respectively, the stress at maximum force, the modulus of elasticity, and the deformation at rupture.

Analysis of the ultimate tensile strength results presented in Figure 3 allows for a comprehensive assessment of the influence of NFC, masterbatch (MB), and PEG on the mechanical performance of PLA-based composites. The formulations with and without PEG show that the isolated incorporation of masterbatch or cellulose nanofibrils does not significantly increase tensile strength. This result highlights the limitations of reinforcement efficiency when additives are used individually, likely due to poor interfacial adhesion and inadequate dispersion within the hydrophobic PLA matrix, which are well-documented challenges in

Figure 1. Description of steps.

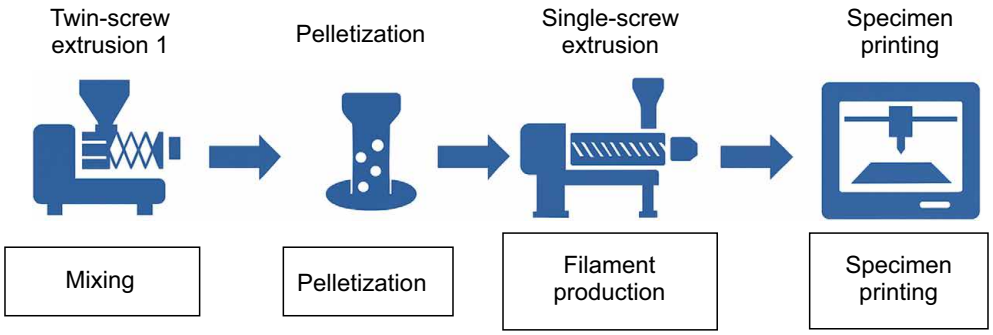


Figure 2. Tensile test specimen of composites obtained by 3D printing.

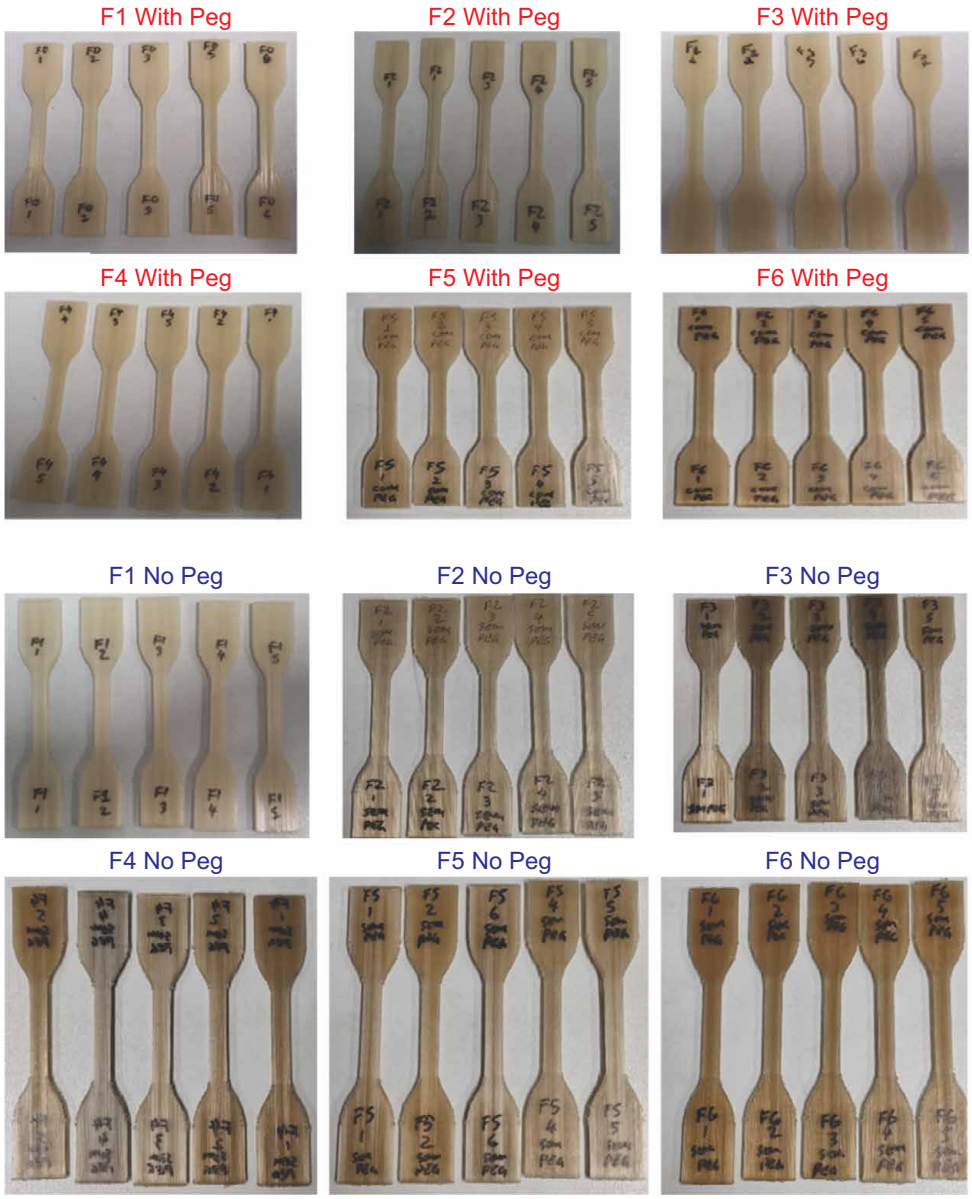


Figure 3. Stress at maximum strength of PLA formulations with and without PEG.

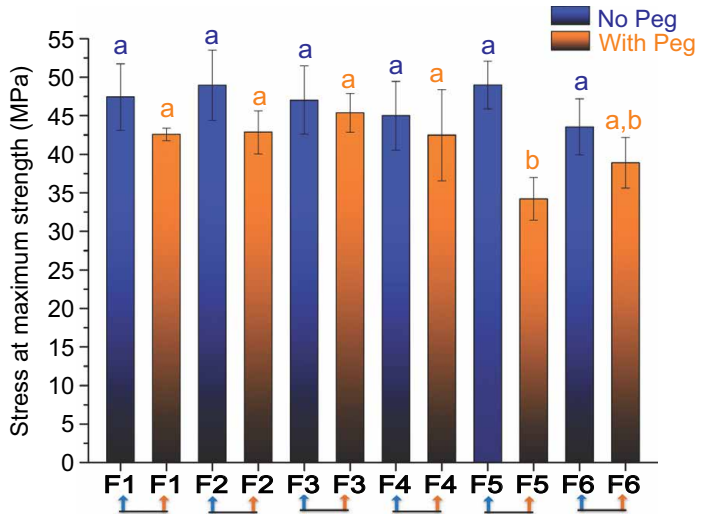


Figure 4. Modulus of elasticity of PLA formulations with and without PEG.

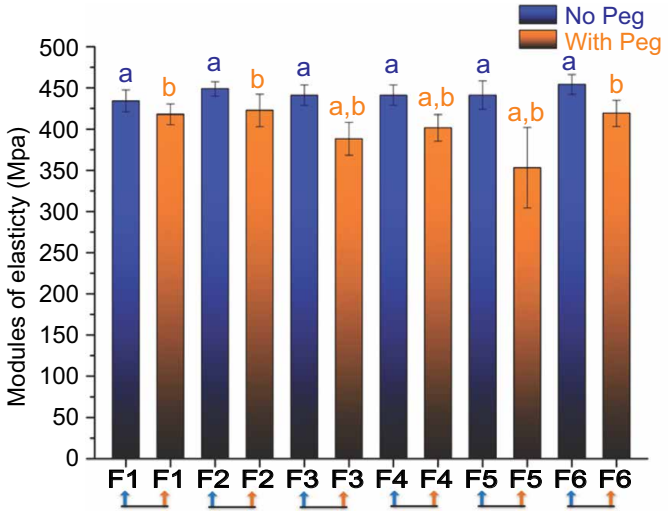
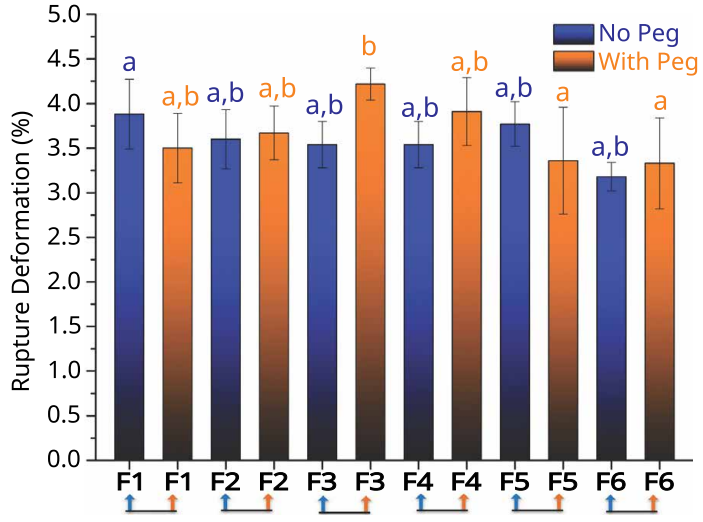


Figure 5. Deformation at break of PLA formulations with and without PEG.



the processing of PLA/nanocellulose composites [10,11].

Formulations F5 and F6, which contain higher NFC contents (1 and 2%, respectively), exhibit a marked reduction in tensile strength, particularly in the presence of PEG. This may be attributed to the difficulty in maintaining dispersion at high NFC loadings, leading to agglomeration and localized strength concentrations that compromise mechanical integrity [7-12].

Interestingly, the PEG-free F6 formulation partially reverses this trend, exhibiting higher strength than its PEG-containing counterpart, as evidenced by the Tukey test, specifically, F5 and F6 with PEG share the Tukey subindex "b," indicating statistically distinct and lower mean values compared to the other samples. This suggests that eliminating PEG in high-NFC systems helps preserve matrix strength and allows the reinforcing effects of nanocellulose to manifest more effectively, provided dispersion is sufficiently controlled [13].

The tensile strength results highlight the critical role of the balance between additive content, dispersion quality, and interfacial compatibility in PLA-based composites. These findings reaffirm the importance of fine-tuning composite formulations to maximize mechanical performance, as corroborated by previous studies on biobased nanocomposites [6-14].

The modulus of elasticity, or Young's modulus, is a key parameter that reflects a material's capacity to withstand deformation when subjected to applied stress. As shown in Figure 4, the results clearly demonstrate the effects of NFC content, the presence of PEG, and the synergy between additives on the stiffness of PLA composites.

Formulation F6 (PLA + 2% NFC, no PEG) exhibited the highest Young modulus (454.42 MPa), highlighting the reinforcing effect of nanocellulose at higher concentrations in the absence of plasticizer. This finding is in line with previous studies indicating that well-dispersed NFCs increase the brittleness of PLA due to their high aspect ratio and strong hydrogen bonding network [6,7]. The absence of PEG, in this case, preserves the interfacial tension between the matrix and the nanofibrils, maximizing the reinforcement potential. Similarly, formulation F2 (PLA + MB, no NFC) achieved a high modulus (449.02 MPa), indicating that the functionalized additives on the masterbatch surface can promote polymer chain alignment or reduce segmental mobility, thus increasing the difficulty. However, the addition of PEG to this formulation (F2 with PEG) reduces the modulus to 422.76 MPa, which is consistent with the known plasticizing behavior of PEG, which increases chain mobility and reduces intermolecular interactions [6-16].

The effect of PEG becomes even more pronounced in formulation F5 (PLA + MB + 1% NFC), where the modulus dropped from 441.42 MPa to 353.28 MPa after PEG incorporation. This sharp drop reveals the challenge of achieving a favorable balance between reinforcement and plasticization. It is likely that, at this NFC concentration, PEG not only interferes with NFC dispersion but also increases chain flexibility to the point of weakening the composite structure, a characteristic also observed in other NFC-PLA systems with poor interfacial control [13,14].

On the other hand, formulation F3 (PLA + NFC, no masterbatch) in the presence of PEG resulted in one of the lowest impairment values (388.37 MPa), confirming that, in the absence of compatibilizers, PEG can impair reinforcement efficiency. The lack of interfacial adhesion PLA/NFC, combined with the mobility-enhancing effect of PEG, results in deformable and less rigid composite behavior, also reported by Cheng and colleagues (2015) [15] in NFC-reinforced systems without surface treatment.

In summary, the analysis of the elastic modulus between the formulations highlights the critical importance of the balance between reinforcement content, compatibilization, and plasticization. PEG reduces rigidity, especially when interfacial interactions are weak.

Strain at break is a key indicator of ductility, reflecting a material's ability to undergo plastic

deformation before fracture. As illustrated in Figure 5, significant differences in deformation behavior were observed between PLA-based formulations, influenced by the presence of reinforcing agents and plasticizers.

With the isolated addition of masterbatch (F2) or NFC (F3), a reduction in deformation is observed, especially in the absence of PEG. This can be attributed to the increased rigidity and brittleness of the matrix, since the additives, when incorporated, hinder the transfer of polymer chains. When there is no compatibility or specific dispersion, there is a greater formation of stress concentration points that anticipate material rupture. The presence of PEG promotes significant changes. In formulation F3 with PEG, for example, there is a significant increase in strain at break, decreasing the likelihood that PEG acted effectively as a plasticizer, increasing chain mobility, and conferring greater flexibility to the compound. This behavior is consistent with previous studies showing that PEG reduces intermolecular interactions in PLA, increasing ductility [17].

In formulation F3 with PEG, the strain at break increased markedly, confirming the effective plasticizing role of PEG. This result is in line with literature reports that PEG can significantly increase ductility by disrupting PLA's intermolecular interactions and increasing polymer chain flexibility [6,7]. This formulation achieved the highest ductility among all samples, demonstrating the synergistic effect of plasticization in an unreinforced matrix.

Formulations F5 and F6, which incorporated 1 and 2% NFC, respectively, revealed interesting contrasts. F5 with PEG showed increased strain compared to its PEG-free counterpart, although to a lesser extent than F3. This suggests that the plasticizing effect of PEG is partially impaired by the increased NFC content. For F6 with PEG, the strain dropped to the lowest value among all samples. This counterproductive result is consistent with the appearance of reinforcement supersaturation, where high NFC loadings, especially when poorly dispersed, create microstructural defects that act as failure initiation sites, impairing ductility [7-17].

Interestingly, F6 without PEG exhibited greater strain than F6 with PEG. Although counterintuitive, this may reflect the formation of a more consistent internal NFC network in the absence of PEG, providing a better monetary response before rupture. PEG, in this case, may have disrupted this network, leading to premature failure due to microphase separation or void formation during deformation, a phenomenon observed in polymer nanocomposites with low matrix-filler compatibility [13-17].

Overall, these findings demonstrate that ductility in PLA composites is governed by a delicate balance between plasticization and reinforcement. While PEG enhances flexibility, its effect is significantly influenced by the type, concentration, and dispersion of reinforcing agents. The most ductile behavior was observed in F3 with PEG, while the most brittle occurred in F6 with PEG, highlighting the critical role of formulation design in optimizing mechanical performance.

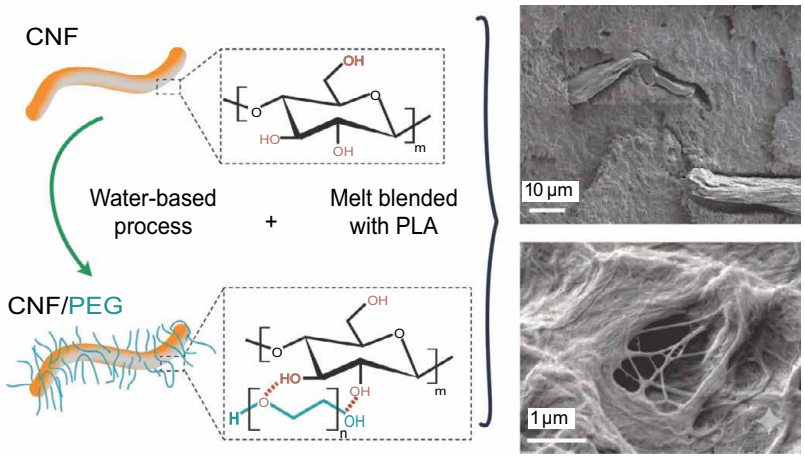
Figure 6 shows a schematic representation of hydrogen bonding interactions PEG-NFC, promoting a well-entangled reinforcement network.

Optical microscopy examination of the fractured surfaces of tensile test specimens (Figure 7) reveals that the samples containing PEG exhibit a more ductile fracture morphology, characterized by stretched and deformed regions, whereas the samples without PEG display a comparatively brittle fracture appearance.

The melt-processing of cellulose nanofibril/ polylactide bionanocomposites via a sustainable polyethylene glycol-based carrier system [6] (Figure 6), it can be concluded that the effective dispersion of NFC in PLA through the incorporation of PEG as a carrier was critical to the mechanical and structural performance of the developed composites.

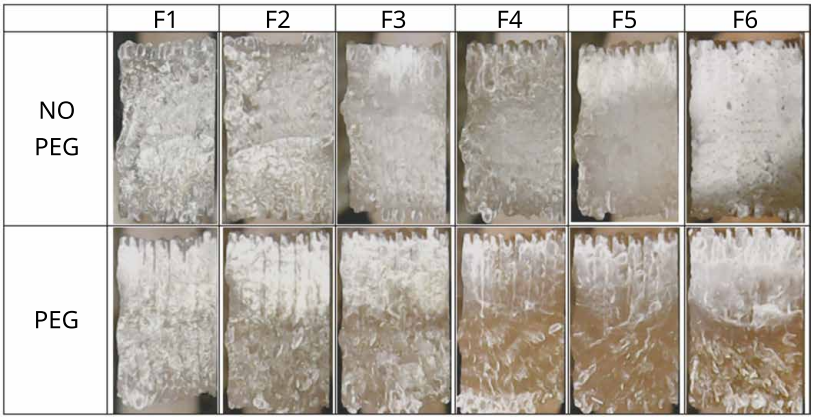
The analyses showed that moderate levels of PEG enable the formation of oxygen bonds

Figure 6. Hydrogen bonding interactions PEG-NFC.



Adapted from Cailloux and colleagues (2019) [6].

Figure 7. Optical microscopy of fractured surfaces of tensile test specimens.



between the NFC and the polymer matrix, which facilitates the dispersion of the nanofibrils and prevents their agglomeration, one of the greatest challenges in the formulation of melt-formed nanocomposites. Formulations F3 and F4, with balanced NFC and PEG contents, stood out for presenting good strength and deformation, demonstrating a well-structured network. On the other hand, formulations with higher NFC concentrations (such as F5 and F6 with PEG) showed poor performance, likely due to network saturation and excessive plasticization.

Thus, the study confirms that the use of masterbatch and NFC with PEG is an effective strategy for improving compatibility and dispersion in PLA, optimizing the material's mechanical properties. This system represents a viable advancement for the production of biocomposites with balanced performance, aligning sustainability, processability, and structural efficiency.

Conclusion

This study demonstrated the effectiveness of using polyethylene glycol (PEG) as a carrier for the dispersion of cellulose nanofibrils (NFC) in a polylactide (PLA) matrix, enabling the production of bionanocomposites through melt processing. The masterbatch formulation with PEG was designed to be strategic in promoting intermolecular interactions, such as protective bonds, which favored compatibility between components and minimized the typical challenges of NFC agglomeration.

The mechanical results indicated that formulations with moderate NFC and PEG contents, especially F3 and F4, demonstrated the best balance between strength, damage, and deformation, revealing optimized performance for applications that unlock flexibility and structural integrity. Conversely, excess NFC and plasticizer compromised performance due to agglomeration and excessive plasticization, highlighting the need of composition control.

Acknowledgement

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References

1. Dufresne A. Cellulose nanomaterials as green nanoreinforcements for polymer nanocomposites. Philos Trans A Math Phys Eng Sci. 2018;376(2112):20170040. doi:10.1098/rsta.2017.0040.
2. Ghasemi S, et al. Development of nanocellulose-reinforced PLA nanocomposite by using maleated PLA (PLA-g-MA). J Thermoplast Compos Mater. 2018;31(8):1090-1101. doi:10.1177/0892705717734.
3. Kurita H, et al. Tensile properties of mechanically-defibrated cellulose nanofiber-reinforced polylactic acid matrix composites fabricated by fused deposition modeling. Trans Nanjing Univ Aeronaut Astronaut. 2021.
4. Wang C, et al. Reinforcement of polylactic acid for fused deposition modeling process with nanoparticles treated bamboo powder. Polymers. 2019;11(7):1146. doi:10.3390/polym11071146.
5. Somphol W, et al. Effect of polyethylene glycol in nanocellulose/PLA composites. Key Eng Mater. 2019;821:89-95. doi:10.4028/www.scientific.net/KEM.821.89
6. Cailloux J, et al. Melt-processing of cellulose nanofibril/polylactide bionanocomposites via a sustainable polyethylene glycol-based carrier system. Carbohydr Polym. 2019;224:115188. doi:10.1016/j.carbpol.2019.115188.
7. Clarkson CM, et al. Crystallization kinetics and morphology of small concentrations of cellulose nanofibrils and cellulose nanocrystals melt-compounded into poly(lactic acid) with plasticizer. Polymer. 2020;187:122101. doi:10.1016/j.polymer.2019.122101.
8. Khoo RZ, Ismail H, Chow WS. Thermal and morphological properties of poly(lactic acid)/nanocellulose nanocomposites. Procedia Chem. 2016;19:788-794. doi:10.1016/j.proche.2016.03.086.
9. Petousis M, et al. Multifunctional material extrusion 3D-printed antibacterial polylactic acid with binary inclusions: the effect of cuprous oxide and cellulose nanofibers. Fibers. 2022;10(6):52. doi:10.3390/fib10060052.
10. Bikiaris ND, et al. Recent advances in the investigation of poly(lactic acid) nanocomposites: incorporation of various nanofillers and their properties and applications. Polymers. 2023;15(5):1196. doi:10.3390/polym15051196.
11. Khalil HPSA, et al. A review on nanocellulosic fibres as new material for sustainable packaging: process and applications. Renew Sustain Energy Rev. 2016;64:823-836. doi:10.1016/j.rser.2016.06.072.
12. Kaushik A, Singh M. Isolation and characterization of cellulose nanofibrils from wheat straw using steam explosion coupled with high shear homogenization. Carbohydr Res. 2011;346(1):76-85. doi:10.1016/j.carres.2010.10.020.
13. Chanda S, Bajwa DS. A review of current physical techniques for dispersion of cellulose nanomaterials in polymer matrices. Rev Adv Mater Sci. 2021;60(1):325-341. doi:10.1515/rams-2021-0023.
14. Olonisakin K, et al. Key improvements in interfacial adhesion and dispersion of fibers/fillers in polymer matrix composites: focus on PLA matrix composites. Compos Interfaces. 2022;29(10):1071-1120. doi:10.1080/09276440.2021.1878441.
15. Cheng D, et al. Adsorption of polyethylene glycol onto cellulose nanocrystals to improve its dispersity. Carbohydr Polym. 2015;123:157-163. doi:10.1016/j.carbpol.2015.01.035.
16. Lazaro-Hdez C, et al. Enhancing polylactic acid films with polyethylene glycol-based plasticizers: a reactive extrusion approach. Macromol Rapid Commun. 2025:2401130. doi:10.1002/marc.202401130.
17. Bajwa D, et al. Influence of biobased plasticizers on 3D printed polylactic acid composites filled with sustainable biofiller. Ind Crops Prod. 2021;173:114132. doi:10.1016/j.indcrop.2021.114132.

Influence of Processing Conditions on the Colloidal Stability of CNCs from Coconut Fiber

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The production of cellulose nanocrystals (CNCs) from agro-industrial residues represents a sustainable and technically feasible alternative, promoting the reuse of low-cost materials with high cellulose content. This study evaluated the effect of two bleaching routes of coconut fiber — using buffered sodium hypochlorite (PC) and alkaline hydrogen peroxide (PP) — on the colloidal properties of CNC suspensions obtained by sulfuric acid hydrolysis. Four different reaction conditions were tested, combining acid concentration, time, and temperature, in the following configurations: 40_25_35, 60_25_35, 40_40_35, and 60_40_35. The samples were characterized by dynamic light scattering (DLS) and zeta potential analysis, assessing average particle size (Z-Average), polydispersity index (PdI), and colloidal stability. The results showed that sample PC60_40_35 had the best performance, with a reduced size (255.4 nm), a moderate PdI (0.412), and a high absolute zeta potential (−32.36 mV), indicating good electrostatic stability and a homogeneous particle size distribution. Samples such as PP40_25_35 and PP60_25_35 also exhibited intermediate particle sizes (≈530 nm), but with lower stability. Overall, the PC bleaching route, combined with higher acid concentration and longer reaction time, favored the production of CNCs with more suitable colloidal properties, demonstrating the combined impact of treatments on suspension quality. These data have practical relevance and can be used to optimize future industrial processes for producing nanocellulose.
Keywords: Cellulose Nanocrystals. Coconut Fibers. Bleaching. Acid Hydrolysis. Colloidal Stability.

Growing concerns over the environmental impacts of the exploitation of non-renewable resources have driven a global shift toward more sustainable production models, notably the circular economy. This approach emphasizes the valorization of waste and by- products as feedstocks for new processes, thereby promoting resource recovery and minimizing waste generation. Within the agro-industrial sector, the utilization of lignocellulosic residues has gained prominence as a strategic pathway to develop renewable materials, such as cellulose nanocrystals (CNCs), which offer advanced functional properties and potential applications across a wide range of industrial sectors [1].

Green coconut fiber, abundantly available in Brazil, is often discarded after the consumption of the water and inner pulp, thus becoming a significant environmental residue. Although it exhibits an intermediate cellulose content — ranging from 23% to 43%, depending on factors such as soil conditions, maturation stage, and prior treatments — this fiber has been investigated as an alternative source for the production of cellulose nanocrystals (CNCs), primarily due to its wide availability and low cost [2,3]. CNCs are particles characterized by high crystallinity, rigidity, and colloidal stability, offering significant potential to replace synthetic materials in composites, packaging, coatings, and colloidal systems [4].

The production of cellulose nanocrystals (CNCs) generally involves a sequence of steps, including cellulose bleaching and acid hydrolysis. The bleaching stage aims to remove lignin and hemicelluloses, thereby facilitating acid access to the fiber's amorphous regions. The choice of bleaching agents directly affects the composition, structure, and reactivity of the cellulosic pulp. Buffered sodium hypochlorite (PC) and alkaline hydrogen peroxide (PP) are commonly applied bleaching routes, each exhibiting distinct mechanisms of action, making it essential to understand their specific effects on nanocrystal extraction [5].

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In addition, sulfuric acid hydrolysis requires strict control of variables such as concentration, time, and temperature, as these factors directly influence the morphology, degree of sulfation, and stability of the final product. Improperly adjusted parameters may result in excessive cellulose degradation or the formation of unstable particles with poor colloidal quality [6]. Therefore, the careful selection of hydrolysis conditions, combined with the choice of pretreatment, is crucial to obtaining CNCs with physicochemical properties tailored to their intended applications.

The first colloidal analyses performed in aqueous suspension provide key indicators of the quality of CNC suspensions. Dynamic light scattering (DLS) allows for the measurement of the average particle size (Z-Average) and the polydispersity index (PdI), which indicate the degree of uniformity of the suspension. Zeta potential measurements, in turn, provide information on the electrostatic stability of particles in liquid media, being essential for predicting material behavior in formulations and during storage. In general, absolute zeta potential values greater than 30 mV are associated with more stable suspensions [7]. Therefore, the integrated analysis of bleaching routes, hydrolysis parameters, and colloidal properties in suspension is essential to optimize the CNC production process and ensure materials with suitable quality for technological applications.

Material and Methods

Green coconut fiber was first washed, oven-dried (Quimis Q314M222) at 60 °C for 24 h, and milled using a Wiley-type mill (Tecnal, model R-TE- 650/1). The resulting material was sieved (Bertel, AGT.P) through a 40-mesh screen (~425 µm) and subjected to a mercerization step, using 60 g of fiber in a 2% (w/v) sodium hydroxide solution under constant stirring (IKA, C-MAG HS4) at 80 °C. This procedure was repeated for 4 cycles to partially remove hemicelluloses and promote cell wall swelling, thereby facilitating access to the cellulosic constituents.

Following this step, the mercerized pulp was divided and subjected to two distinct chemical bleaching routes:

PC route: treatment with 1.7% (v/v) sodium hypochlorite buffered with acetate solution (pH ≈ 4.45), carried out at 80 °C for 6 h under constant stirring (IKA, C-MAG HS4).

PP route: treatment with 16% (v/v) hydrogen peroxide buffered with 5% (w/v) sodium hydroxide, carried out at 55 °C for 2 h under constant stirring (IKA, C-MAG HS4).

In both routes, the post-bleaching material was filtered, dried (Quimis, Q314M222), and milled (Ariete, Universal PRO Grinder).

Acid hydrolysis was carried out in a water bath at 35 °C, using 2 g of bleached pulp in 40 mL of sulfuric acid (H_2SO_4), with variations in concentration and reaction time as indicated in Table 1. At the end of the reaction time, 40 mL of cold water was added to quench the reaction, and the hydrolyzed solution was placed in an ice-water bath until it reached 20 °C. The sample was then centrifuged (Hettich, Rotina 380R) at 4400 rpm for 10 min, with 5 mL of distilled water added to the Falcon tubes after each cycle until a final volume of 20 mL was reached. The supernatants were dialyzed against a cellulose membrane (model D9402, Sigma-Aldrich) until neutral pH was reached.

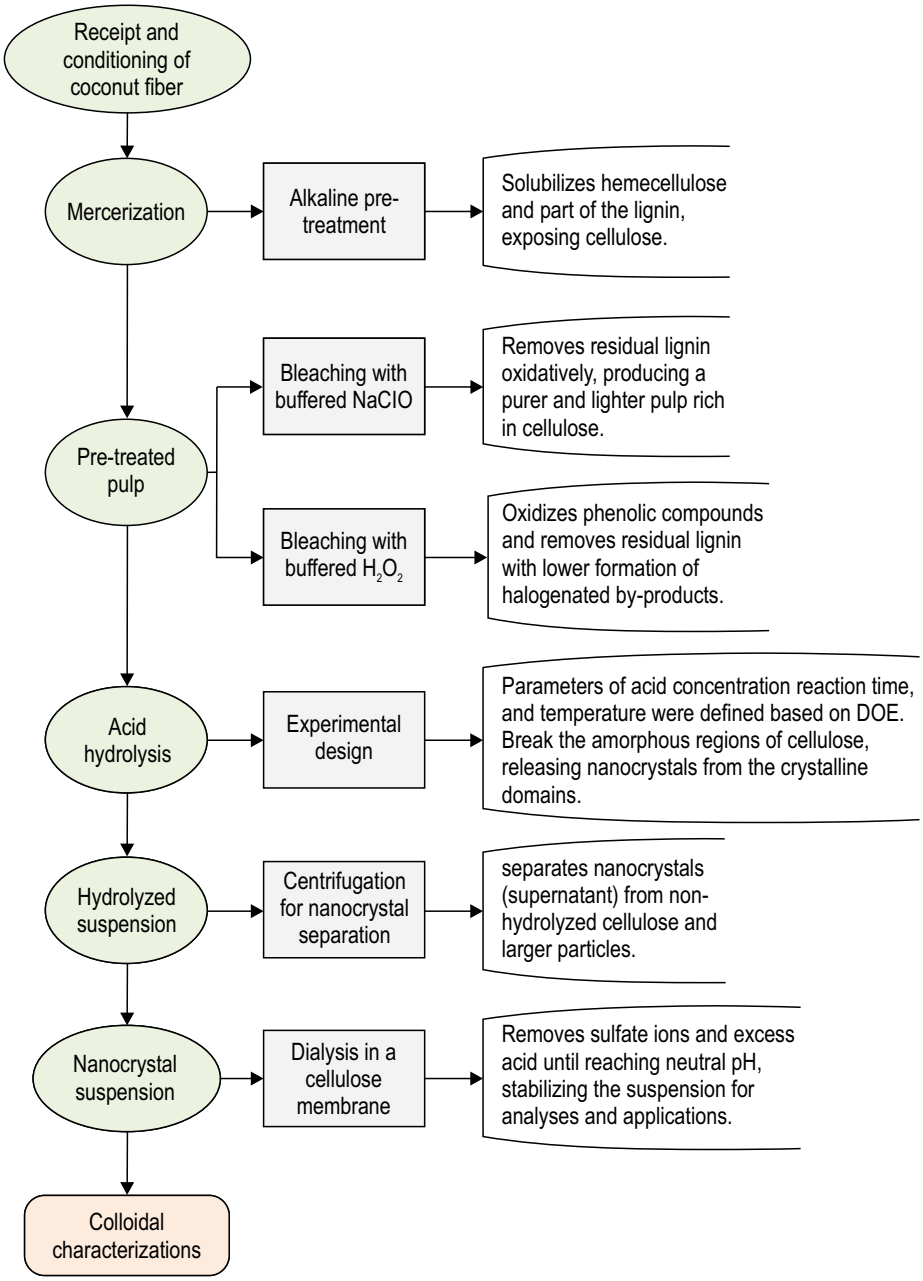
A flowchart (Figure 1) of the process for obtaining the nanocrystals is provided below.

The colloidal characterization of cellulose nanocrystal (CNC) suspensions was performed using Dynamic Light Scattering (DLS) and zeta potential analysis on a Zetasizer Ultra (Malvern Panalytical) equipped with a Non-Invasive Back Scatter (NIBS) system and a fixed backscatter detector angle of 173°. Samples were previously redispersed in ultrapure water (resistivity ≥ 18.2 MΩ·cm), standardized to 0.01% (w/v), and subjected to indirect sonication for 10 min in an ultrasonic bath (50/60 Hz) to disrupt agglomerates.

Table 1. Reaction conditions applied for the acid hydrolysis of bleached coconut fibers.

Sample Code	H_2SO_4 concentration (%)	Reaction time (min)	Temperature (°C)
40_25_35	40	25	35
60_25_35	60	25	35
40_40_35	40	40	35
60_40_35	60	40	35

Figure 1. Simplified flowchart of the methodology for obtaining cellulose nanocrystals and the objective of each step.



The average particle size (Z- Average), polydispersity index (PdI), and zeta potential were obtained from three independent measurements per sample at 25 °C, using disposable cells suitable for each analysis.

Results and Discussion

The colloidal evaluation of cellulose nanocrystal (CNC) suspensions obtained from coconut fiber enabled the identification of the direct effects of pretreatment steps (bleaching) and hydrolysis conditions on the material's physicochemical parameters. Table 2 presents the results for zeta potential, average particle size (Z-Average), and polydispersity index (PdI) for the eight samples obtained from the PC and PP routes.

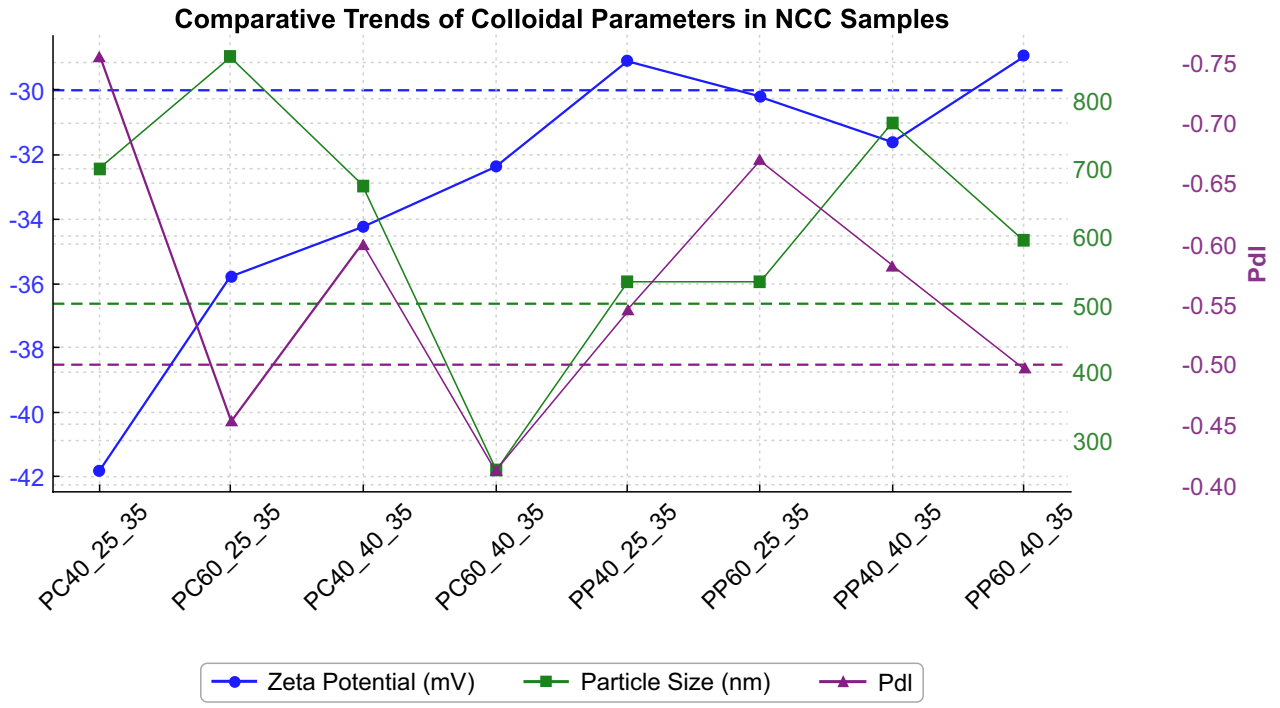
According to the literature, the ideal criteria for CNCs in suspension indicate that absolute zeta potentials greater than 30 mV indicate good electrostatic stability [7]. At the same time, average particle sizes of 100-500 nm suggest effective degradation of amorphous regions while preserving the integrity of crystalline domains [8]. Additionally, PdI values below 0.3 indicate monodispersion; however, materials obtained from agro-industrial residues often exhibit values up to 0.5, which are still considered acceptable [3]. Figure 1 presents an integrated comparison of the three main colloidal parameters analyzed: zeta potential, particle size, and polydispersity index (PdI). The combined analysis facilitates the identification of the sample with the best performance in terms of stability, uniformity, and hydrolysis efficiency (Figure 2).

In this context, the PC60_40_35 sample exhibited superior performance, with a zeta potential of –32.36 mV, a particle size of 255.4 nm, and a PdI of 0.412. This profile suggests a stable suspension, with relatively homogeneous particles and dimensions comparable to those reported for sisal residue, corn husk, and rice husk fibers, which have a lignocellulosic composition similar to that of coconut fiber. When compared to CNCs obtained from rice straw [9], which presented significantly smaller dimensions (11.2–30.7 nm in width and 117–270 nm in length, as determined by microscopy), the CNCs produced in this study (255.4 nm hydrodynamic diameter, –32.36 mV zeta potential, PdI = 0.412) exhibited particle sizes closer to the reported lengths but considerably larger widths, which is expected given that DLS measures hydrodynamic diameters of aggregates in suspension. In relation to nanocellulose derived from sugarcane bagasse [10], which was reported to have particle sizes within the nanorange by DLS without specific values in the abstract, the CNCs from coconut fiber showed a tendency toward larger hydrodynamic sizes, possibly due to residual lignin and hemicelluloses or the specific hydrolysis conditions employed. Nevertheless, the zeta potential obtained (–32.36 mV) indicates good

Table 2. Results of colloidal stability, particle size, and dispersion analyses of nanocrystals in suspension.

Sample Code	Zeta Potential (mV)	Particle Size (d.nm)	Polydispersity Index (PdI)
PC40_25_35	-41.80	699.0	0.756
PC60_25_35	-35.76	865.5	0.453
PC40_40_35	-34.22	673.9	0.600
PC60_40_35	-32.36	255.4	0.412
PP40_25_35	-29.08	533.9	0.545
PP60_25_35	-30.19	534.6	0.669
PP40_40_35	-31.59	765.5	0.582
PP60_40_35	-28.93	593.6	0.496

Figure 2. Comparative trends of colloidal parameters in NCC samples.



electrostatic stability, comparable to or potentially superior to that observed for CNCs from both rice straw and sugarcane bagasse, highlighting the potential of coconut fiber as a competitive lignocellulosic source for CNC production.

The influence of the bleaching route was also evident. The PC route (buffered hypochlorite) provided greater electrostatic stability across all tested conditions. This can be attributed to more efficient lignin removal and the exposure of reactive sites on the fiber surface, which facilitate acid action during hydrolysis. In contrast, the PP route, although also oxidative, yielded zeta potential values below |30| mV, suggesting a lower density of negative surface charges. When compared to CNCs obtained from cotton via different bleaching methods followed by acid or enzymatic hydrolysis [11], the CNCs produced in this study demonstrated a level of electrostatic stability above the |30| mV threshold, indicating a high density of negative surface charges and good suspension stability. In the cotton-based study, variations in bleaching method were shown to influence hydrodynamic properties and surface charge density significantly. However, specific zeta potential values were not provided in the abstract. Considering this, the stability observed in the coconut fiber CNCs produced under the PC60_40_35 condition suggests that the chosen bleaching and hydrolysis parameters effectively enhanced the surface charge density, achieving stability levels likely comparable to or greater than those reported for cotton-derived CNCs, despite differences in raw material composition and fiber morphology.

Regarding the polydispersity index, none of the samples reached the ideal value of < 0.3. However, the values observed for samples PC60_40_35 (0.412), PC60_25_35 (0.453), and PP60_40_35 (0.496) indicate a reasonably acceptable distribution for systems derived from complex fibers. In the present study, the CNCs obtained from green coconut fiber indicate a moderately narrow particle size distribution and an acceptable level of monodispersion for CNCs derived from complex lignocellulosic fibers. In contrast, studies involving coconut shell powder or particles as fillers in polymeric matrices [12,

13] do not report quantitative PdI values; however, SEM analyses reveal agglomeration and an uneven distribution of filler particles, suggesting a high degree of polydispersity at the microscale. These observations align with the understanding that achieving low polydispersity is more feasible in nanocellulose suspensions, where surface chemistry and colloidal stabilization mechanisms can be optimized, than in particulate polymer composites, where interfacial adhesion and particle wetting dominate dispersion behavior.

Additionally, the reduction in average particle size observed for the PC60_40_35 sample suggests that the combination of a high acid concentration and a prolonged reaction time, together with effective pretreatment, promoted the selective degradation of amorphous regions without compromising the crystalline structure. Thus, the results demonstrate that the PC route combined with the 60_40_35 condition produces CNCs with superior colloidal characteristics compared to the other conditions, making it the most promising option for future applications in films, coatings, or nanocomposites. The similarity between the results obtained and those reported in the literature for lignocellulosic residues confirms the feasibility of coconut fiber as an alternative source of cellulose nanocrystals.

Conclusion

The objective of this study was successfully achieved by producing cellulose nanocrystals (CNCs) from coconut fiber, using different bleaching routes and acid hydrolysis conditions, followed by a comprehensive evaluation of their colloidal properties. The results demonstrated that the PC bleaching route, when combined with the 60_40_35 hydrolysis condition, provided CNCs with greater electrostatic stability, adequate particle size distribution, and dimensions comparable to those reported for other lignocellulosic residues.

These findings confirm the potential of coconut fiber as an alternative, sustainable source for CNC production, with promising applicability in films, coatings, and nanocomposite materials. Furthermore, future studies should focus on incorporating these CNCs into polymeric matrices to evaluate their reinforcing effect, mechanical performance, and compatibility with biodegradable polymers, thus expanding their potential for industrial applications in sustainable packaging, advanced composites, and functional coatings.

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References

1. Geyer R, Jambeck JR, Law KL. Production, use, and fate of all plastics ever made. Sci Adv. 2017;3(7):e1700782. doi:10.1126/sciadv.1700782.
2. Jonoobi M, Oladi R, Davoudpour Y, Oksman K. Different preparation methods and properties of nanostructured cellulose from various natural resources and residues: a review. Cellulose. 2015;22(2):935-969. doi:10.1007/s10570-015-0551-0.
3. Souza ES, Brito RA, Campos NLF, Ramos DP. Aplicação da fibra de coco no processo de isolamento termo acústico. Rev Gestão Sustent Ambient. 2015;4:233-245. doi:10.19177/rgsa.v4e02015233-245.
4. Moon RJ, et al. Cellulose nanomaterials review: structure, properties and nanocomposites. Chem Soc Rev. 2011;40(7):3941-3994. doi:10.1039/c0cs00108b.
5. Zhang Y, et al. Bleaching of pulp: efficiency and impact on cellulose structure. Carbohydr Polym. 2018;189:442-450. doi:10.1016/j.carbpol.2018.02.045.
6. Eichhorn SJ, et al. Current international research into cellulose nanofibres and nanocomposites. J Mater Sci. 2010;45:1-33. doi:10.1007/s10853-009-3874-0.
7. Gellerstedt G, Hon DNS, Shiraishi N. Pulping chemistry. In: Wood and cellulosic chemistry. New York: Marcel Dekker; 2001. p. 859-905.
8. Soleimani S, Heydari A, Fattahi M. Isolation and characterization of cellulose nanocrystals from waste cotton fibers using sulfuric acid hydrolysis. Starch Stärke. 2022;74(11-12):e2200159. doi:10.1002/star.202200159.
9. Lu P, Hsieh YL. Preparation and characterization of cellulose nanocrystals from rice straw. Carbohydr Polym. 2012;87(1):564-573. doi:10.1016/j.carbpol.2011.08.022.

10. Mandal A, Chakrabarty D. Isolation of nanocellulose from waste sugarcane bagasse and its characterization. Carbohydr Polym. 2011;86(3):1291-1299.doi:10.1016/j.carbpol.2011.06.030.
11. Rahman MM, Ghasemi N, Kurniawan A, et al. A comparative study of the impact of the bleaching method on the production and characterization of cotton-origin nanocrystalline cellulose by acid and enzymatic hydrolysis. Polymers. 2023;15(16):3446. doi:10.3390/polym15163446.
12. Joseph PV, Mathew G, Joseph K, et al. Mechanical, thermal and morphological behaviors of coconut shell powder filled PU/PS biocomposites. Adv Mater Res. 2010;123-125:331-334. doi:10.4028/www.scientific.net/AMR.123-125.331
13. Agunsoye JO, Talabi SI, Samuel SO. Study of mechanical behaviour of coconut shell reinforced polymer matrix composite. J Miner Mater Charact Eng. 2012;11(8):774-779. doi:10.4236/jmmce.2012.118065.

Thruster Allocation for Underactuated ROVs: Simulation and Real-World Implementation

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Underwater exploration gained prominence starting in the 1950s with the emergence of the first ROVs (Remotely Operated Vehicles). Among their categories, observation ROVs stand out for their ability to collect data in hard-to-reach environments. In this context, the OpenROV — an open-source mini ROV with a modular architecture — was studied. One of the units had mechanical damage and serial communication failures with the original electronics, requiring a retrofit process. Additionally, a thruster allocation study was conducted to evaluate the platform's movement in both simulation and real operation. Through this technique, it was possible to verify that the current configuration allows movements along the surge, heave, and yaw axes, with correspondence between simulation and actual actuation. The study contributed to the analysis of the system's degrees of freedom and its potential navigability in an aquatic environment.
Keywords: OpenROV. Thruster Allocation. Simulation. Underwater Vehicles. Retrofit.

Ocean exploration has driven technological advances since the 20th century. In 1953, Dimitri Rebikoff developed the POODLE, considered the first Remotely Operated Vehicle (ROV) in history, designed for underwater archaeological research [1]. Despite being pioneering, its impact was limited. In 1961, the United States Navy developed a mobile underwater system that culminated in the CURV (Cable-controlled Underwater Research Vehicle), a landmark for the evolution of ROVs [1]. These vehicles have been widely used in various applications ever since. ROVs are commonly classified by their functionality. Observation ROVs are built for data and image collection. Work-class ROVs are equipped with manipulators for interventions. Special-use ROVs are designed for specific missions [1]. ROVs are particularly valuable in scientific research, as they enable data collection in inhospitable and hard-to-reach environments.

Over time, advances in technology enabled the creation of smaller, more accessible solutions. Based on this evolution, platforms like OpenROV emerged [2]. Two OpenRovs models 2.8 [3] in the Robotics and Autonomous Systems Laboratory are used for educational and research purposes. However, one of the units was damaged and a system retrofit process was proposed. Then, an investigation into thruster allocation was conducted, a technique to properly distribute forces among thrusters, enabling the vehicle to perform the desired movements [4]. Therefore, the implementation of thruster allocation has become a promising line of research as the vehicle is undergoing a redesign due to its damaged structure. These vehicles can be classified according to the relationship between the number of actuators and their degrees of freedom. When the number of actuators is fewer than the six typical degrees of freedom of these vehicles, the system is considered underactuated [4]. This group includes the OpenROV, which has only three thrusters and only moves in the surge, heave, and yaw directions. The relevance of this classification for the study of thruster allocation in ROVs lies in the fact that designing a control system capable of stabilization, trajectory tracking, and trajectory control in underactuated vehicles is a non-trivial task [4]. Such systems require handling physical and dynamic constraints and, in many cases, the adoption of nonlinear control strategies. Thruster allocation, in turn, provides an approach that maximizes the potential of the available actuators,

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allowing the vehicle to operate efficiently within a reduced set of target movements. This makes it feasible to design simpler and more effective control strategies that take into account the physical limitations of the system. Therefore, the goal of this work is to evaluate the technique's functionality in the OpenROV's motion control system by implementing it on both a physical prototype and in a simulated environment.

Materials and Method

In this study, it has been necessary to create a simulation environment using the Gazebo Ignition Fortress platform [5] and its buoyancy plugins, aiming to simulate the effect of water on the robot. To make the environment more realistic, the inertia matrix (1) of the OpenROV 3D model, extracted from the Fusion 360 modeling software, was used:

$$\mathbf{I} = \begin{bmatrix} 77.42 & 0 & 0 \\ 0 & 77.42 & 0 \\ 0 & 0 & 77.42 \end{bmatrix} \quad \mathrm{kg \cdot m^2} \qquad (1)$$

A mass of 8 kg was estimated for the simulated model, including the thrusters and complete electronics. The vehicle's weight must be equal to the buoyant force generated by (2):

$$F_b = \rho \cdot V \cdot g \qquad (2)$$

By doing this, the vehicle achieves neutral buoyancy, which keeps it stable from sinking or floating [6]. The value of ρ for water density was set to 1,000 kg/m³, the standard for water; V is the volume of the ROV, and g is gravity. A native plugin was used to implement these calculations based on the provided data [7]. Besides Gazebo, the ROS2 Humble Hawksbill software was used, specifically the "ros2_control" package suite [8]. This module is responsible for managing controllers and hardware interfaces and integrating them with both Gazebo and the physical robot. The use of these resources enabled the application of the thruster allocation matrix. The matrix calculation process was carried out considering the linear thruster model described by equation (3) found in [4]:

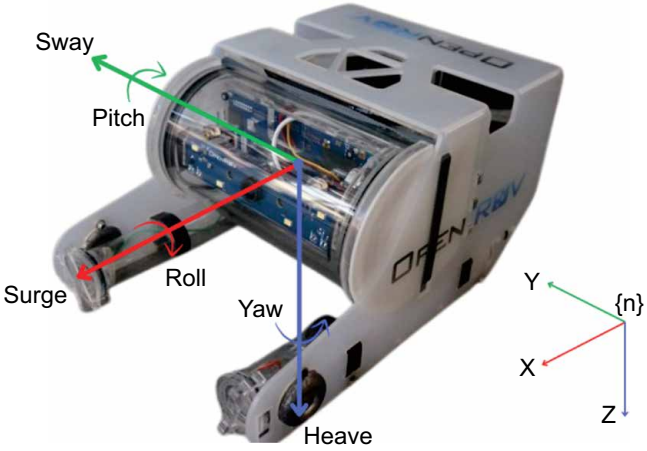
$$F = Ku \qquad (3)$$

Where u is a matrix containing the control signals sent to the thrusters, and K is the diagonal matrix containing the force coefficients of each thruster. To obtain the allocation matrix, formula (4) is used:

$$\tau = T(\alpha)F = T(\alpha)Ku \qquad (4)$$

Where τ is the vector of generalized forces and moments, and T(α) is the thruster configuration matrix dependent on the steering angles α, according to the NED (North-East-Down) reference frame, standard for underwater vehicles, as shown in Figure 1.

Figura 1. Coordinate system in NED's pattern.



The vector τ is given by (5):

$$\tau = \begin{bmatrix} f \\ r \times f \end{bmatrix} = \begin{bmatrix} F_x \\ F_y \\ F_z \\ F_z l_y - F_y l_z \\ F_x l_z - F_z l_x \\ F_y l_x - F_x l_y \end{bmatrix} \qquad (2)$$

To use Equation (5), it is necessary to measure the distances of the thrusters relative to the robot's center of mass. The measured values are shown in the Table 1.

Table 1. Moment arms of the 3 thrusters of the OpenROV relative to the center of mass.

Ti	lxi **(mm)**	lyi **(mm)**	lzi **(mm)**
$T1$	-26	45	0
$T2$	-	2	26
$T3$	-26	-45	0

By applying (5) for each thruster, the following matrix is obtained, where each column represents a thruster:

$$T(\alpha) = \begin{bmatrix} -1.0 & 0.0 & -1.0 \\ 0.0 & 0.0 & 0.0 \\ 0.0 & 1.0 & 0.0 \\ 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 \\ -0.045 & 0.0 & 0.045 \end{bmatrix} \quad (6)$$

The implementation of the allocation is given by Equation (7):

$$u = K^{-1} T^{-1} \tau \quad (7)$$

Given a control signal, a vector of corresponding values is obtained to be applied to each thruster. Since the OpenROV matrix is non-square, the Moore-Penrose method must be used to compute the pseudo-inverse T^{+}:

$$T^{+} = TT(TTT)^{-1} \quad (8)$$

$$u = K^{-1} T^{+} \tau \quad (9)$$

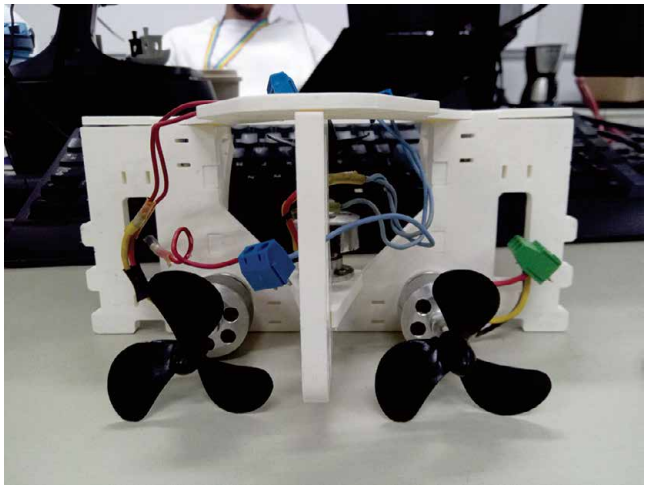
These computations were automated using a controller to handle the specified calculations. An OpenROV platform retrofit was initiated to verify the elements that were described outside of the simulated environment. This procedure was required because of the platform's damage. Figure 2 illustrates how the thrusters' supporting framework was broken.

Figure 2. The acrylic structure supporting the thrusters was damaged.

The CAD files available on the OpenROV GitHub platform [9] were used, and all parts were 3D printed in ABS material, as shown in Figure 3.

Therefore, because of the mechanical capabilities and water resistance, the ABS polymer was selected for submerged applications [10]. Additionally, serial communication with

Figure 3. Thruster support structure printed in ABS.



the original electronic board for thruster control was not possible. This limitation also required the development of a new board with new electronic components. For testing, PWM signals were sent via serial commands to activate the motors using an Arduino Nano, a breadboard, and a bench power supply that provided the 12 V required to power the motor ESCs. The experiments with the robot were not conducted underwater.

Results and Discussion

The results of the allocation calculations aimed to enable movements in surge, heave, and yaw. It is worth noting that, initially, tests to verify this were conducted in the Gazebo Ignition simulation environment. Table 2 shows the values applied to the thrusters, derived from the previous calculations.

Table 2. Force values in Newtons generated by the thrusters activated with a control signal value of 1.

Ti	Surge	Sway	Heave	Roll	Pitch	Yaw
P1	-0.5	0	0	0	0	-0.5
P2	0	0	1	0	0	0
P3	-0.5	0	0	0	0	0

The absence of pictures displaying a top perspective and the precise location of the thrusters in relation to the NED coordinate system led to the creation of Figure 4. A rear perspective of the thrusters' position is shown in Figure 5 more clearly.

The graphics in Figures 6, 7, and 8 provide a clearer visual representation of the numbers found in Table 2.

Figure 6 illustrates how the right and left thrusters engage with forces of the same magnitude, direction, and sensation when the ROV is instructed to travel in the direction of the surge. The ROV will move forward thanks to the combined force of both.

Figure 7 illustrates the activation of the vertical thruster while the others remained inactive in response to an instruction in the heave direction. The upward and downward motions of the ROV are generated by the thruster forces.

The yaw movement is presented in Figure 8, where the left and right thrusters were activated with forces of equal magnitude but in opposite directions. The resulting force from this combination is responsible for rotating the ROV around its axis, as illustrated in Figure 9.

Following the simulation testing, the allocation matrix was implemented on the actual hardware, and the same procedure for gathering data was followed, as seen in Figure 10.

Figure 4. Top view of the OpenROV.

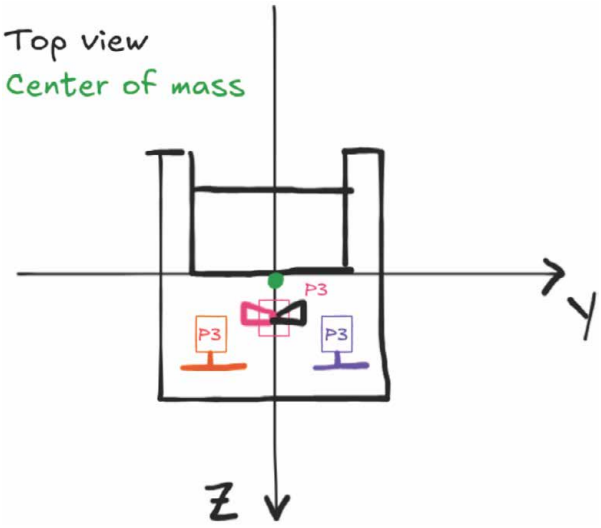
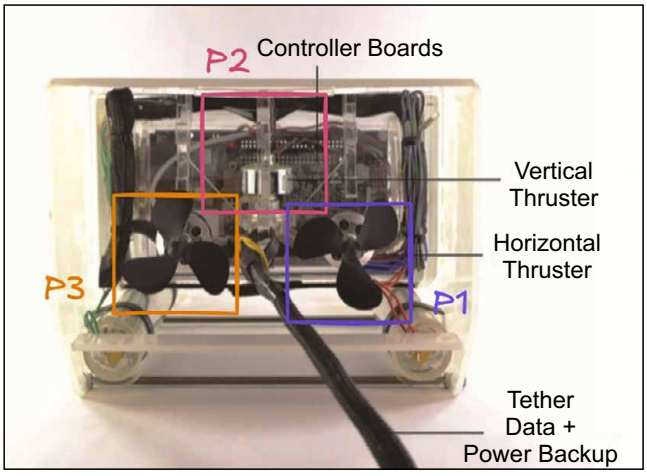


Figure 5. Rear view of the OpenROV.



Source: NADDAF-SH and colleagues (2018).

Figure 6. Control signal in X (surge) *vs*. right and left thrusters being activated with the same force.

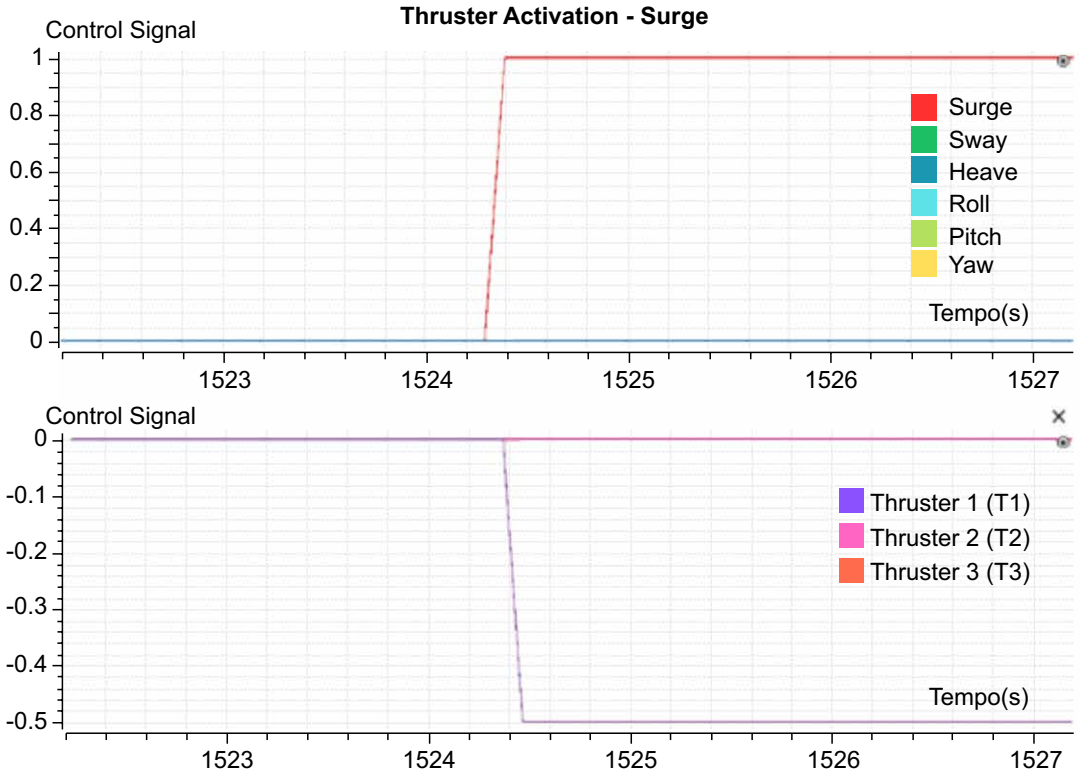


Figure 7. Control signal in the heave *vs*. vertical thruster being activated.

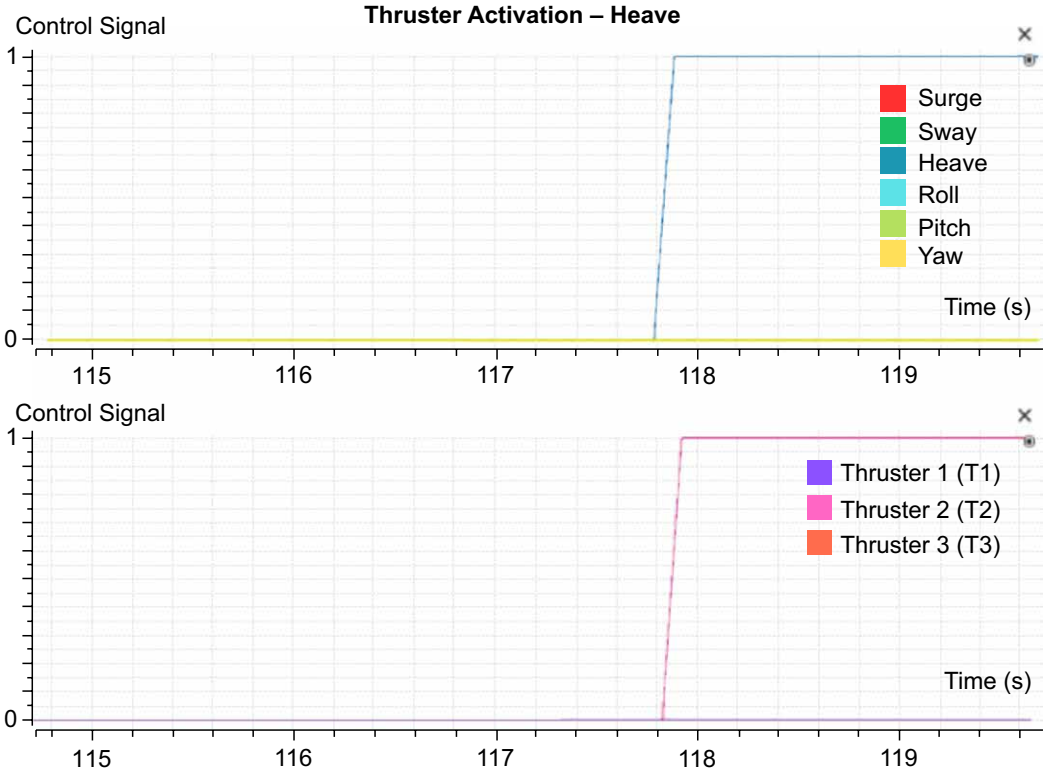


Figure 8. Control signal in yaw *vs*. right and left thrusters being activated with equal magnitude but opposite forces.

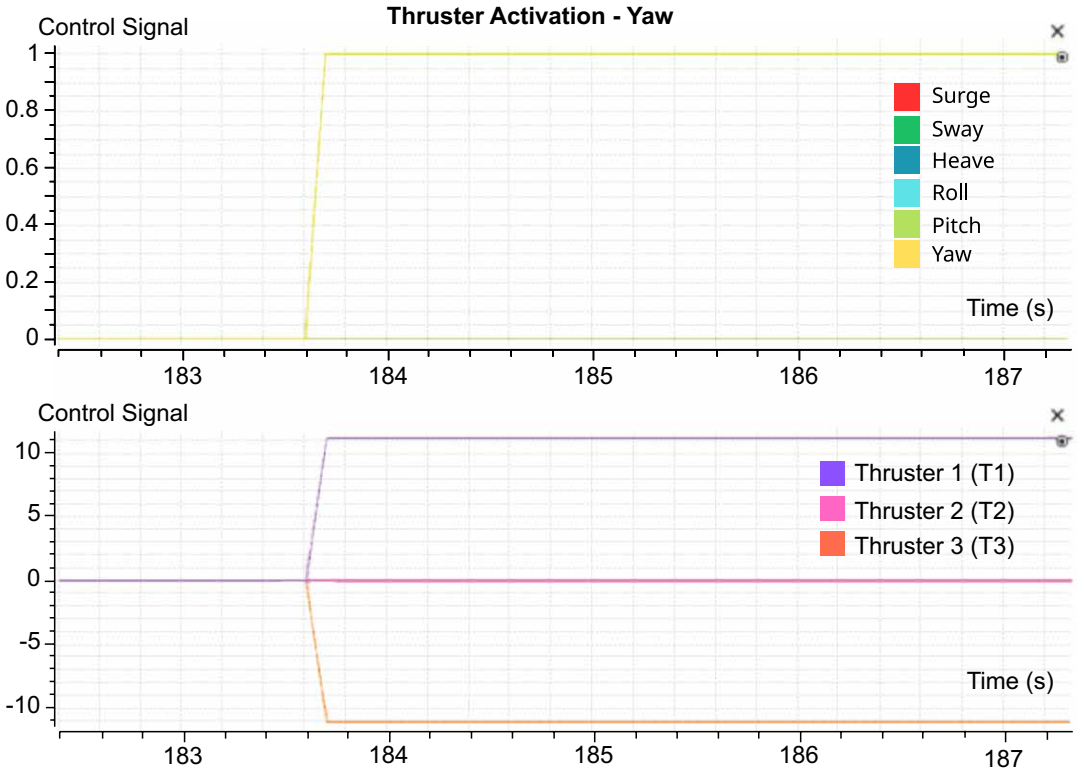


Figure 9. OpenROV in simulation performing yaw to the left.

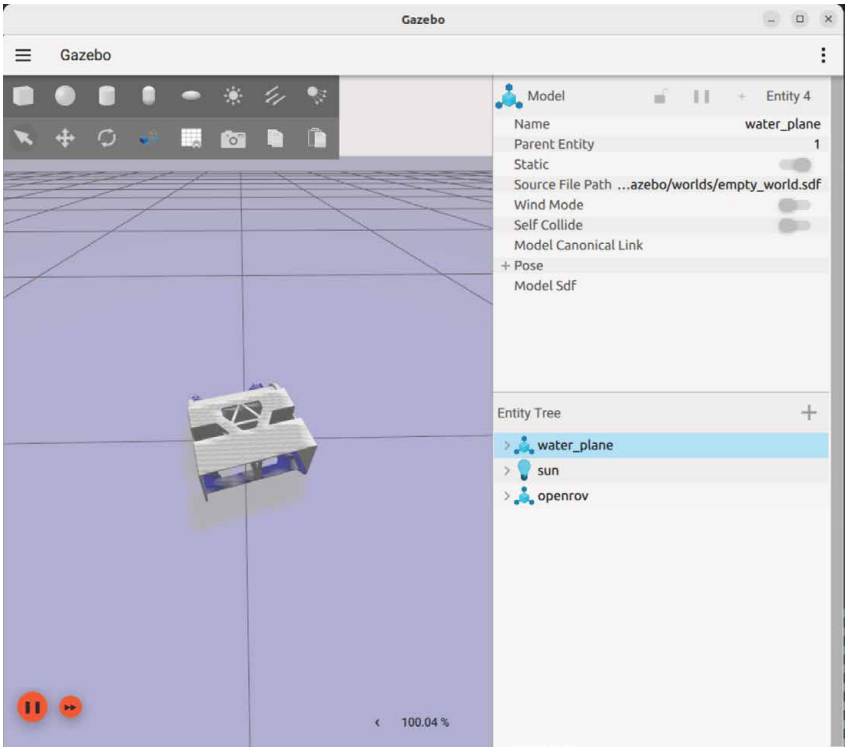
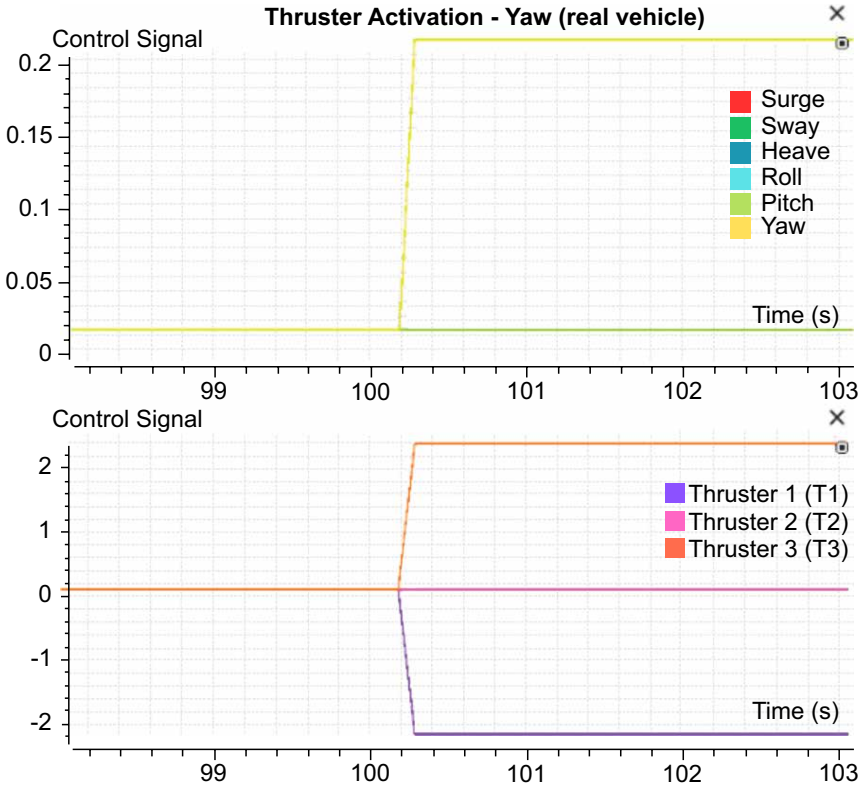


Figure 10. Control signal in yaw *vs*. right and left thrusters being activated with equal magnitude but opposite forces on the real vehicle.



The yaw movement presented the same response in the simulation, Figure 10. This outcome was confirmed in every other movement, proving the efficacy of both the method, with the real vehicle hardware and the simulation environment.

Conclusion

It was possible to determine the OpenROV controllable degrees of freedom by comparing and implementing truster allocation in both simulated and real-world settings. This confirmed that the OpenROV could move along the yaw, heave and surge axes even with fewer thrusters. The concordance between simulation and real-world tests showed the efficacy of the thruster operation technique.

These results provide a foundation for future improvements, such as submerged ROV testing and control of the current axes using a PID controller for robot stabilization, as well as the integration of inertial measurement units (IMUs) to carry out other research activities.

References

1. Christ RD, Wernli RL. The ROV manual. Amsterdam: Elsevier; 2011.
2. Munz J. Design and implementation of software for the ROV Neptunus [dissertation]. [place unknown]: [publisher unknown]; [year unknown]. Available from: https://ntnuopen.ntnu.no/ntnu-xmlui/bitstream/handle/11250/2364892/13963_FULLTEXT.pdf
3. OpenROV Dozuk. Wayback Machine [Internet]. Available from: https://web.archive.org/web/*/https://openrov.dozuki.com/
4. Fossen TI. Handbook of marine craft hydrodynamics and motion control. Hoboken (NJ): John Wiley & Sons; 2021.
5. Ignition Fortress — Gazebo fortress documentation [Internet]. Available from: https://gazebosim.org/docs/fortress/install/
6. Marzbanrad A, et al. Design, construction and control of a remotely operated vehicle (ROV). In: Volume 7: dynamic systems and control; mechatronics and intelligent machines, parts A and B; 2011 Jan 1.
7. Gazebo Sim [Internet]. Available from: https://gazebosim.org/api/sim/8/theory_buoyancy.html

8. Getting started — ROS2_control: humble documentation [Internet]. 2024 Mar. Available from: https://control.ros.org/humble/doc/getting_started/getting_started.html
9. OpenROV. OpenROV hardware: hardware for OpenROV, including lasercut parts and diagrams [Internet]. Available from: https://github.com/OpenROV/openrov-hardware
10. Leite M, et al. Mechanical properties and water absorption of surface modified ABS 3D printed by fused deposition modelling. Rapid Prototyp J. 2018;24(1):195-203.
11. Naddaf-Sh M, Mahdi M, Myler H, Zargarzadeh H. Design and implementation of an assistive real-time red lionfish detection system for AUV/ROVs. Complexity. 2018;2018:1-10.

Spectral Analysis of Irregular Sea Waves

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Accurate modeling of ocean wave behavior is a critical component in ensuring the safety, efficiency, and longevity of offshore structures and naval systems. The marine environment is inherently complex, characterized by highly irregular and dynamic wave patterns influenced by a wide range of environmental factors, including wind, tides, and ocean currents. These variables introduce significant challenges in predicting wave-induced forces and their impact on floating and fixed offshore platforms, vessels, and energy harvesting devices. To address these challenges, spectral wave analysis has emerged as a fundamental approach, offering engineers a robust framework for interpreting and simulating wave behavior with enhanced precision. Among the numerical techniques employed in spectral analysis, the Fast Fourier Transform (FFT) stands out due to its computational efficiency and ability to decompose complex, time-domain wave signals into their constituent frequency components. This transformation enables a clearer understanding of the temporal and spatial characteristics of wave motion, which is essential for the design of resilient and adaptive offshore systems. In this context, the present study investigates the application of Fourier series and FFT in modeling irregular sea wave patterns, emphasizing their effectiveness in representing periodic and quasi-periodic phenomena through the superposition of sinusoidal functions. The methodology of this study involves the acquisition of real-world wave data from the Rede Ondas project, followed by signal processing using FFT implemented in spreadsheet software. The resulting complex coefficients were analyzed to extract amplitude and frequency information, enabling the construction of a spectral profile of the wave field. Key wave parameters such as significant wave height and peak frequency were identified, providing insights into the dynamic loading conditions that offshore structures may encounter.

Keywords: Irregular Waves. Fast Fourier Transformation. Offshore.

Spectral wave analysis is a fundamental tool in the design and evaluation of offshore structures, ships, and tidal energy generation systems. The oscillatory behavior of ocean waves induces dynamic loads that can significantly affect the structural integrity and operational stability of these systems. In addition to contributing to structural instability, wave-induced motions are critical for assessing oceanographic data relevant to engineering applications. Understanding these dynamics through spectral methods enables more accurate modeling and enhances the reliability of marine infrastructure [1-3].

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Marine waves are typically considered random in nature. However, large wave formations can often be approximated as periodic and regular. In general, wave behavior is modeled using combinations of harmonic oscillations. In simplified scenarios, a single harmonic function may sufficiently represent the wave phenomenon, leading to what are known as regular wave models. Conversely, irregular waves are characterized by the superposition of multiple harmonic components, allowing for a more accurate representation of their complex and stochastic behavior.

Li and colleagues (2012) [4] proposed a study on nonlinear wave-structure interaction using a two-dimensional finite volume approach to assess ship stability. Davidson and colleagues (2015) [5] explored the development of a numerical wave tank through computational fluid dynamics to simulate marine energy generation using floating devices. Wang and colleagues (2015) [6] investigated the

behavior of energy-harvesting buoys under the influence of irregular waves by applying the Fast Fourier Transform (FFT). Tabeshpour et al. (2023) [7] examined the role of the superposition principle of harmonic functions in modeling irregular wave patterns.

Ocean wave measurements are typically conducted using specialized instruments known as wave gauges or wave buoys, which may be equipped with accelerometers or acoustic profilers [8].

Accelerometer-based wave buoys, such as the directional Waverider model, record time series of horizontal and vertical displacements of the buoy, enabling the reconstruction of sea surface motion. These data are processed by onboard microprocessors that compute the frequency spectrum every 30 minutes. Raw and spectral data are transmitted hourly via radio (operating between 25.5 and 35.5 MHz) to a land-based receiving station, which forwards them to a coastal engineering laboratory for processing and dissemination [8].

Alternatively, acoustic profilers such as the ADCP (Acoustic Doppler Current Profiler) utilize the Doppler effect to measure particle displacement within the water column, allowing for the estimation of wave height, direction, and period. These instruments typically operate in burst sampling mode at 2 Hz and can generate detailed directional spectra, which are crucial for accurately characterizing sea state conditions [8].

The processed data enable the calculation of key wave parameters, including the significant wave height (Hs)—defined as the average of the highest one-third of waves in a given record—and the peak period, which corresponds to the most energetic component of the directional spectrum. Wave direction is expressed in degrees, with 0° indicating North, 90° East, and so forth [8].

Theoretical Basis

In vessels, for example, the equation of motion is described from Equation 1 [1]:

$$(m + a_2)x_2'' + b_2x' + c_2x_2 = F_0 sin(\omega t) \quad (1)$$

Where m is the mass of the vessel, $a2$ is the mass of water displaced during movement, $b2$ is the equivalent damping, and $c2$ is the equivalent stiffness caused by buoyancy and gravity.

Ocean waves are generally random in nature; however, larger waves can often be approximated as regular and periodic. Typically, wave modeling involves a combination of harmonic oscillations. In simplified cases, a single harmonic function may be used to represent the phenomenon. These models are referred to as regular waves, characterized by a single harmonic oscillation, whereas irregular waves are represented by the superposition of multiple harmonic functions [9].

The Fast Fourier Transform (FFT) emerges as a powerful tool for characterizing these irregular wave patterns. Several studies in the literature employ this method to obtain frequency-domain responses of specific oscillatory systems.

The Fourier Transform is a mathematical technique that allows the decomposition of a non-harmonic periodic function into a linear combination of harmonic functions. In its analytical approach, the general motion function is equated to a Fourier series, which represents the periodic oscillation, as shown in Equation 2 [10].

$$F(t) = \frac{a_0}{2} + \sum_{j=1}^{\infty} a_j \cos(j\omega t) + \sum_{j=1}^{\infty} b_j \sin(j\omega t) \quad (2)$$

The Fast Fourier Transform (FFT) is a numerical method that requires the input data to consist of a number of ordered pairs in the form of 2n, where n is an integer. This structure ensures computational efficiency and allows the representation of the signal as a harmonic series, as illustrated in Equation 3 [11].

$$X_k = \sum_{j=1}^{\infty} x_m e^{-\frac{i2\pi km}{n}} \quad (3)$$

Where n is the total number of data points and k is the index of each of the applied data points. It is also possible to note the presence of a complex exponential function that is related to a harmonic function as indicated by Euler's theorem represented in Equation 4 [11].

$$e^{ix} = \cos(x) + isin(x) \quad (4)$$

The Fast Fourier Transform (FFT) can be implemented using Excel®, where it is applied to displacement data to extract harmonic components in their complex form. From these complex values, the amplitude of each harmonic is determined by calculating the modulus of the complex number obtained through the Fourier Transform and dividing it by 2/n, where n represents the total number of data points.

To identify the corresponding frequency of each harmonic, the index k of the analyzed component is divided by the total duration of the dataset used in the analysis. This process enables the characterization of wave behavior in the frequency domain, which is essential for evaluating the dynamic response of marine systems.

This article aims to perform a spectral analysis of irregular waves using FFT and evaluate which frequencies have the highest amplitude.

Material and Methods

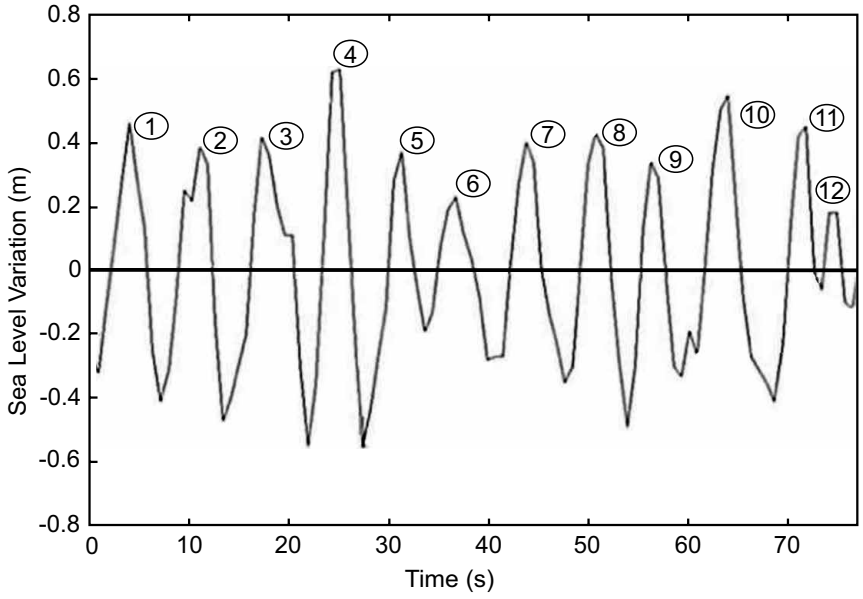
Using data provided by the Rede Ondas (2025) [8], it was possible to analyze measurements recorded by a wave gauge over a 75-second period. These measurements enabled the identification of wave displacements on the ocean surface. Figure 1 illustrates the time-domain response of the recorded wave motion, providing insight into the dynamic behavior of the sea surface during the observation interval.

The data points used in the analysis were extracted from the original graph using the WebPlotDigitizer tool [12]. The image of the graph was first calibrated, allowing the software to accurately interpret the axes and scale. Following calibration, the data points were manually marked on the graph, enabling the tool to convert pixel positions into corresponding numerical values. This process facilitated the reconstruction of the dataset for further analysis.

To improve the accuracy of the extracted data, a filtering process was applied by limiting the RGB deviation to a maximum of 50 units from the selected color range of the graph. This constraint allowed for more precise identification of relevant data points by minimizing noise and inconsistencies in pixel interpretation.

To enable automatic selection of data points, values along the x-axis were sampled at regular

Figure 1. Analysed Graph. Source:



Adapted from Rede Ondas (2025) [9]

intervals of 0.07 seconds. This uniform spacing is essential for the subsequent application of the Fast Fourier Transform (FFT), which requires evenly spaced time-domain data. As a result of this sampling process, a total of 1,101 data points were generated, as shown in Figure 2.

The data were initially imported into a spreadsheet in CSV format, enabling the application of the Fast Fourier Transform (FFT). To meet the computational requirements of the FFT algorithm, the time series was truncated to exactly 1024 data points, as the algorithm is optimized for datasets whose length is a power of two (2n).

The FFT produced a series of complex coefficients representing the spectral components of the waveform, including their respective frequencies and amplitudes. To extract the magnitude of these components, the "IMABS" function was employed, which computes the modulus of each complex number. Subsequently, the resulting values were multiplied by a scaling factor (unspecified in the original excerpt) to adjust the amplitudes for the purpose of quantitative analysis or graphical visualization of the spectral data.

Results and Discution

The spectral graph reveals a dominant harmonic component observed at frequencies of approximately 0.15 Hz exhibiting a peak amplitude of around 0.32 meters. This indicates that marine structures intended for deployment in such environments should avoid natural frequencies within this range to prevent resonance effects. Figure 3 illustrates the frequency-domain representation, highlighting the critical harmonic peaks.

Figure 2. Selected points.

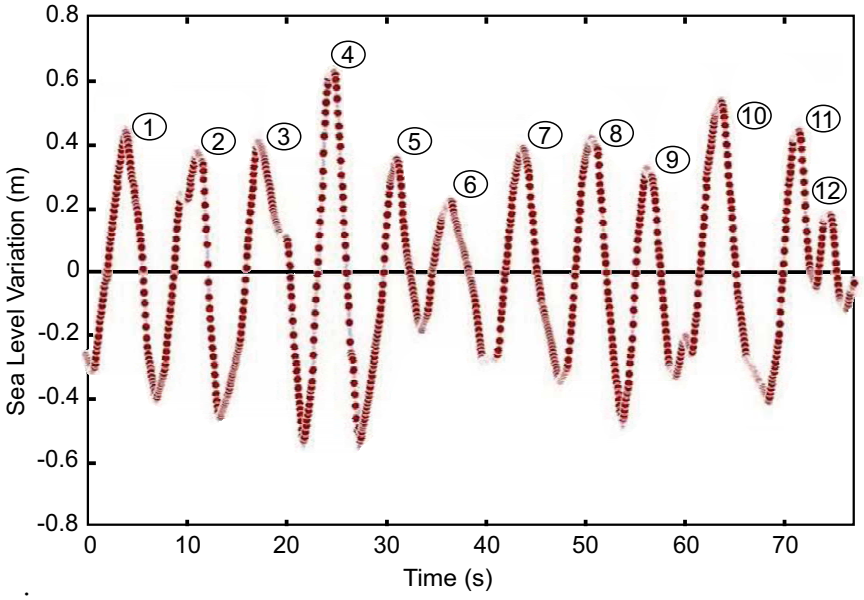
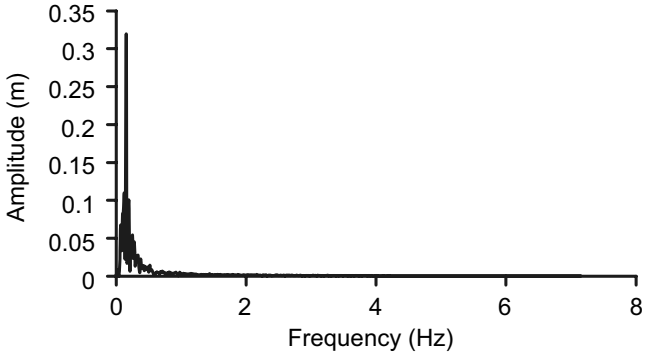


Figure 3. Spectral analysis.



Conclusion

This study highlights the importance of spectral wave analysis in the design and evaluation of marine structures, as well as the effectiveness of the Fast Fourier Transform (FFT) as a method for analyzing wave phenomena in the frequency domain.

Through the spectral analysis of ocean waves, it was observed that the frequency with the highest amplitude is approximately 0.15 Hz. This finding suggests that the natural frequency of equipment intended for operation under such conditions should be carefully designed to avoid resonance within this range.

References

1. Judge CQ. Seakeeping and maneuvering. Curso USNA EN455. Notas de aula; 2019.
2. Wang L, Isberg J. Nonlinear passive control of a wave energy converter subject to constraints in irregular waves. Energies. 2015;8(7):6528-6542. doi:10.3390/en8076528.
3. Lima HGGM, Barbosa ES, Fernandes JA, Barros LM. Análise do efeito do uso do método espectral no estudo da propagação de ondas de águas rasas em meio heterogêneo constituído por óleo e água. In: Congresso Nacional de Pesquisa em Petróleo e Gás – PDPETRO; 4.; 2007; Campinas, SP. Campinas: [s.n.]; 2007.
4. Li Y, Lin M. Regular and irregular wave impacts on floating body. Ocean Eng. 2012;42:93-101. doi:10.1016/j.oceaneng.2012.01.019.
5. Davidson J, Cathelain M, Guillemet L, Le Huec T, Ringwood JV. Implementation of an OpenFOAM numerical wave tank for wave energy experiments. In: Proceedings of the 11th European wave and tidal energy conference; 2015 [cited 2025 Jul 31]. Available from: Maynooth University Research Archive.
6. Wang L, Isberg J. Nonlinear passive control of a wave energy converter subject to constraints in irregular waves. Energies. 2015;8(7):6528-6542. doi:10.3390/en8076528.
7. Tabeshpour MR, Belvasi N. Ocean waves time-series generation: minimum required artificial wave time-series for wave energy converter analysis. J Mar Eng Technol. 2023;22(6):273-283. doi:10.1080/20464177.2023.2197280.
8. Rede Ondas. Aquisição de dados. Universidade Federal do Rio Grande – FURG [Internet]. 2025 [cited 2025 Jul 2]. Available from: https://redeondas.furg.br/pt/aquisicao-de-dados
9. Chakrabarti SK. Handbook of offshore engineering. Amsterdam: Elsevier; 2005. 2 v.
10. Rao SS. Vibrações mecânicas. 4th ed. São Paulo: Pearson Prentice Hall; 2008.
11. Yamaki MD. Introdução ao uso de transformada de Fourier discreta em análise de dados [Internet]. 2024 [cited 2025 Jul 2]. Available from: https://www.researchgate.net/publication/379822428_Introducao_ao_Uso_de_Transformada_de_Fourier_Discreta_em_Analise_de_Dados
12. Rohatgi A. WebPlotDigitizer [Internet]. Automeris; 2024 [cited 2025 Jul 2]. Available from:https://apps.automeris.io/wpd4/

Implementation of Extension Projects in Chemistry at SENAI CIMATEC University: Experience Report

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This article describes the current extension projects in chemistry at SENAI CIMATEC University, which includes innovative and sustainable practices that can generate income for the most vulnerable population, combined with initiatives to enhance student education and promote scientific outreach. All these actions are based on the Sustainable Development Goals – SDGs, such as quality education, reduced inequalities, and sustainable communities. To make this a reality, two projects were implemented: "CIMATEC Saneantes" and "Química Inspira: Um Show de Química". The result is the engagement of undergraduate students with the community, developing scientific knowledge.
Keywords: Extension. Community. Chemistry.

University extension projects promote a fundamental role in the development of undergraduate students, especially in engineering courses, by inseparably integrating teaching, research and community action. As established by Resolution No. 7/2018 of the Ministry of Education [1], extension is now mandatory and curricular, corresponding to at least 10% of the workload of undergraduate courses. This measure reinforces Goal 12.7 of the National Education Plan [2], which aims to ensure the presence of extension practices in the curriculum and promote transformative interaction between university and society. In the context of engineering, this means that future engineers are exposed to real challenges, strengthening not only technical skills, but also critical thinking and social commitment to the demands of the community.

In the same way, projects aimed at community actions bring the future engineer closer to the social reality, enabling him to act in complex contexts and promoting the full exercise of citizenship.

In this context, the development and implementation of extension projects in Chemistry and, consequently, Chemical Engineering, presents itself as a important need of the University, while building a citizen identity and the full demonstration of the importance of Chemistry in all areas of knowledge. Therefore, this article aims to present an experience report of the current extension projects in chemistry at SENAI CIMATEC University.

Projects Developed

Extension activities in chemistry are developed through two projects: CIMATEC Saneantes associated with professional training, and the project Química Inspira: Um Show de Química aimed at scientific dissemination through playful experiments. They were implemented in 2024 and are now completing their first year.

CIMATEC Saneantes Project

The CIMATEC Saneantes extension project represents an important professional training initiative, providing participants with operational knowledge in the manufacture of sanitizing products, such as soap, liquid soap, alcohol gel, bleach, detergent, disinfectant and automotive cleaning products. This practical approach is in line with the trends discussed in events such as ExpoTech, held at SENAI CIMATEC itself, which have reinforced the importance of proximity

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between educational institutions and companies [3]. By offering this type of training, the project not only improves the quality and reliability of the products subsequently manufactured but also opens concrete paths for the generation of employment and income in Salvador and the Metropolitan Region, following the central objectives of university extension aimed at regional and social development.

In addition, the project shows commitment to the circular economy and sustainability through the production of bar soap from waste cooking oil. This type of practice promotes the reduction of improper waste disposal, transforming it into useful products, and stimulates environmental education by demonstrating the importance of correct oil storage, the seriousness of this waste as a polluting agent and a concrete alternative for its reuse as another way to train the population in general.

Finally, by working in the training of entrepreneurs and small producers through production workshops, the project fosters the economic autonomy of the participants and strengthens the connection between the University and the productive sector. The training offered by CIMATEC Saneantes reflects the objective of the extension courses to bring future extension workers closer to the real market, preparing them to innovate, solve community problems and develop products aligned with regional demands. This model of extension action, practiced in partnership with industrial entities such as SENAI itself, is an example of how university extension can contribute to the strengthening of local production chains, circular economy and social inclusion, consolidating itself as a fundamental instrument in the training of complete and engaged professionals.

Project: Química Inspira: Um Show de Química

The Química Inspira: Um Show de Química project is a university extension initiative that seeks to arouse students' interest in science through playful experiments. By promoting scientific dissemination both in basic education schools and within the SENAI CIMATEC University itself, the project follows the model consolidated by similar experiences such as the Química Show at UFScar and the LADIQ at UESB [4,5], where demonstrative experiments arouse creativity and curiosity, consolidating chemical concepts in a sensorial and emotional way.

This strategy through visual, auditory and tactile observation allows students to connect with science even before entering theoretical abstraction, strengthening the natural assimilation of the themes.

The possibility of promoting the Química Inspira project in elementary and high schools of basic education has the potential to expand the reach of scientific dissemination, making chemistry more accessible and interesting for different audiences. Similar projects have already demonstrated positive results in this itinerant format, with significant impacts on student engagement [4,5]. Also, by allowing students to experience the university environment, through visits to SENAI CIMATEC, the project stimulates the scientific vocation and strengthens the bridge between basic education and higher education.

In addition to promoting academic interest, the Química Inspira project offers an opportunity for professional and social development for the extension workers themselves. By planning, structuring and presenting the experiments within the parameters of scientific dissemination, these students improve technical skills, scientific communication and teaching skills. This experience in extension corroborates the principles of Resolution No. 7/2018 of the Ministry of Education [1], which emphasizes the integration between teaching, research and extension as the essence of higher education. Thus, Química Inspira project establishes itself as a strategic tool to inspire the next generation of scientists and engineers, making chemistry an inspiring and transformative experience.

Results

CIMATEC Saneantes Project

The CIMATEC Saneantes project involved the participation of 12 students from the Chemical Engineering course from SENAI CIMATEC University over 1 year, and during this period it was possible for students to study and develop 20 practice scripts for the manufacture of sanitizing and cosmetic products, such as: soap, liquid soap, alcohol gel, bleach, detergent, disinfectant and automotive cleaning products. It was also possible to carry out an in-depth study of the manufacture of soap from waste cooking oil (Figure 1). To develop this knowledge, it was necessary for students to understand the saponification reaction of the Organic Chemistry discipline and understand the function of a strong base and a fatty acid. In Figure 2 it is possible to verify the soap produced.

The great gain for the students was the improvement of their basic laboratory techniques, being an opportunity to expand the knowledge acquired in the disciplines. In this way, it was also possible to generate a sense of belonging to the extension students, because since the first semester of graduation they have already been taken to the laboratory to experience the project.

While the instructional scripts were developed, it was possible to hold the first workshops for the manufacture of soap from used oil and other sanitizing products. The first workshop was held with students from SESI's integrated education (Figure 3), and the second workshop was held as part of the Environment Week held at the IES itself. It was a moment in which we took the first steps of university extension and, currently, we have started negotiations to carry out the professional training workshop for chemistry technicians in Salvador and the Metropolitan Region.

Project: "Química Inspira: Um Show de Química"

The Química Inspira project involved the participation of 8 students from the Chemical

Figure 1. Extension studentts manufacturing detergent.

Figure 2. Soaps produced by extension students.

Figure 3. Workshop on the production of soap from waste cooking oil for SESI students.

Engineering course at SENAI CIMATEC University, from the most varied semesters, over 1 year. In this process, it was possible to validate several playful experiments to promote scientific dissemination. It was an opportunity to encourage and motivate the extension students

themselves, but, in addition, it was possible to develop a presentation for the schools, and we held a workshop with students from the Mestre Paulo dos Anjos school, located in Bairro da Paz – Salvador – Bahia. It was a very rich initial moment for all involved, promoting university extension and citizenship, as the extension workers were able to understand the reality in which visitors lived and thus recognize privileges and discuss issues for a more egalitarian and just society.

This project was also involved with the student recruitment sector promoted by the SENAI CIMATEC University, in which high school students from different schools in the city participated in the CIMATEC Experience, an opportunity in which we carried out some experiments and the extension workers talked a little about their experience.

Challenges, Achievements and Next Steps

Currently, the projects have six extension students and one extension scholarship holder, after a partnership with the extension program Public Office of Engineering and Architecture, which is linked to the university extension center (Figure 4).

The great challenge associated with the two projects was precisely regarding the resources needed for the acquisition of reagents and the use of the University's chemistry didactic laboratory that supports all practical disciplines, whether in technical education or undergraduate. Numerous practical project activities need to be postponed due to the lack of an adequate schedule in the laboratory and resources. However, it was possible to obtain financial support through a public notice carried out by the University itself, the Public Notice for the Promotion of Teaching Initiatives 2024, in which we competed with other projects to obtain a financial resource of R$2500.

Despite of all that, even with a little significant resource regarding the needs of projects associated with chemical practice, we managed, over 1 year of existence, to promote the participation of 20 undergraduate students in workshops in

Figure 4. The current team of extension students.

remarkable events such as the Environment Week and our own workshops that involved the external public and, mainly, students of basic education from a school in the community.

Also, the possibility of creating an extension program in chemistry will strengthen the projects, as it will be possible to apply for more extension scholarships and various other resources through funding notices. These practices make the program more robust and can attract students from the most diverse engineering degrees at the University itself.

Conclusion

Both the CIMATEC Saneantes and Química Inspira projects are successful examples of how university extension in chemistry can consolidate itself as a strategic axis in academic training and social transformation. Their participatory methodologies, applied content, and strong community component make them not only pedagogical projects, but true agents of scientific citizenship, social innovation, and strengthening the links between science, technology, and society.

In addition, these initiatives dialogue directly with the Sustainable Development Goals: they contribute to SDG 4 (Quality Education) by offering scientific training from basic education to

graduation; for SDG 10 (Reduction of Inequalities) by generating income opportunities and access to knowledge in vulnerable populations; to SDG 11 (Sustainable Cities and Communities) and SDG 12 (Responsible Production and Consumption) by encouraging circular economy practices and conscious consumption [7].

The prospects for improvements begin with the implementation of indicators to assess the impact of the project, the strengthening of partnerships with schools, city halls and local companies for better accessibility, teaching materials in online formats to expand the reach and enable asynchronous learning and the offer of more workshops with the communities served.

Acknowledgement

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References

1. Brazil. Ministry of Education. Resolution No. 7, of December 18, 2018. Brasília (DF): Ministry of Education; 2018.
2. Brazil. Ministry of Education. National education plan: Law No. 13005/2014 [Internet]. Brasília (DF): MEC; 2014.
3. Expotech Bahia [Internet]. Salvador (BA): Expotech; 2025. Available from: https://expotechbahia.com.br/
4. Silva JG, Santos EB, Costa MES, Coelho EF, Ferro HS, Cavalcanti LAMN, et al. O show da química: uma maneira lúdica de divulgação científica da química para estudantes do ensino fundamental e médio. Anais CIET: Horizonte [Internet]. 2024;5(1). Available from: https://ciet.ufscar.br/submissao/index.php/ciet/article/view/2186
5. LADIQ. Laboratório de divulgação química [Internet]. 2025 [cited 2025 Jul 27]. Available from: https://ladiq.blogspot.com/
6. Nações Unidas no Brasil. Objetivos de desenvolvimento sustentável [Internet]. 2025. Available from: https://brasil.un.org/pt-br/sdgs

Developing System Dynamic Modeling for Risk Management in Water Utilities: A Proposal for Framework Based on a Sistematic Review

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This work systematically reviewed articles published between 2019 and 2024 on system dynamics approaches in water resource management, focusing on drinking water supply, seeking to identify advances in models which address risks or risk management in water resources. The aim was to verify whether the models contribute to corporate risk management in companies which provide water supply services. Based on an adaptation of the PRISMA methodology, forty articles published in journals were selected. Main results: all articles presented a case study; only one article presented a water utility as a case study; 20% of the studies entailed risks in modeling and 15% included stakeholders and experts in the formulation of the models; 45% of the studies have adopted both qualitative and quantitative system dynamics modeling; 53% of the studies were produced on the Asian continent, especially in China; 47% of the quantitative models are integrated with other types of modeling; 91% of the models have undergone a verification method. Vensim is the most widely used software in studies. At last, based on these results and identified gaps, a system dynamics model structure was proposed for corporate risk management in drinking water supply companies.
Keywords: Water Resources Management. Water Supply. Risk Management. Stakeholders. System Dynamics.

Water is associated with all aspects of life, such as human health, food security, economic development, and ecological balance [1]. The demand for fresh water is increasing, however, several factors make its future availability uncertain, such as population growth, water pollution, economic progress, changes in land use, and climate change [2].

Decades of misuse, mismanagement, overextraction, contamination of both fresh surface and groundwater affects your supply, thus aggravating water stress [3]. The comprehensive and viable long-term universalization of access to water and sanitation services represents one of the most crucial struggles of the 21st century [4].

The concern to guarantee access to drinking water for all is stated in Sustainable Development Goal 6: drinking water and sanitation, which is defined in its target 6.1: "by 2030, achieve universal and equitable access to safe drinking water for all" [3].

Natural resource scarcity, such as water and food, is among the ten global risks predicted to aggravate over the next ten years. The risk of water scarcity manifests itself as water insecurity on a local, regional or global level. This risk is the result of human overexploitation and mismanagement of critical natural resources, climate change and/or a lack of adequate infrastructure [5].

From a system perspective, risk is inherent and is a function of the states of the system and its environment. Risk can be defined as a measure of the likelihood and severity of consequences, and the vulnerability to hazards and resilience vectors of a system are postulated to be a function of the input, occurrence, and states of that system, which have an impact on the consequences [6].

Urban water supply companies operate in a complex environment, including regulatory, economic (financial), social, environmental issues, and must manage a wide range of risks.

Therefore, water resource managers must manage, for example, environmental risks (floods, water pollution, water scarcity, etc.) and, at the

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same time, improve the quality of the environment, health, and well-being of the population [7].

Evidently, water resource systems are complex and the system dynamics approach has been used to address this complexity, driven by multiple interactions arising from climate change and social-economic stress factors [8]. This enables a holistic understanding of water resource systems [9].

Jay Forester created System Dynamics (SD) in the 1960s. In the 1970s, it was first applied to water resource management. The number of research articles applying SD to water resource management has increased substantially, specially since 2013, and this popularity demonstrates the growing interest of researchers around the world in using the SD modeling approach to manage complex water resource systems [8].

System dynamics-based models for water resources management are intended to evaluate policies or answer the "what if?" questions [2], aiding decision making. In addition, SD models enable the participation of stakeholders from the definition of the scope of the problem to the model validation process [8].

Stakeholders can be defined as actors who have an interest in the issue under consideration, who are affected by the issue, or who, due to their position, have or can have an active or passive influence on decision-making [10].

The system dynamics approach allows for the risk assessment, i.e. the impact of different elements (subsystems) on the safety of the system, as well as the achievement of dynamic and quantitative forecasts, thus compensating for the shortcomings of qualitative linear, static, and chain assessment methods [11].

The purpose of this article is to carry out a systematic review of literature, covering the state of the art in the period 2019-2024, works on the application of SD modeling to water resource management, specially works on urban drinking water supply, with an emphasis on models that address risks or risk management. Moreover, to verify whether stakeholders and/or specialists are involved in water resources modeling. Taking into consideration the most recent publications on the problem, the analysis was filtered in the period 2019-2024 as a filter to restrict the sample size. Furthermore, literature reviews with similar themes were identified in periods prior to this work, such as Phan et. al. (2021) [8].

The aim is to answer the following research question: Is it possible to propose a model structure based on the system dynamics approach for risk management in water supply companies?

Thus, this study includes the selection and systematic analysis of studies, characterizing them based on the definition of requirements. At last, the objective is to propose a modeling framework for dealing with risks and their management in the environment of water supply companies.

Materials and Methods

For the qualitative selection of articles, a systematic literature review was conducted, setting a clear purpose, research question, a defined research approach, and establishing inclusion and exclusion criteria for articles [12]. For the systematic review, the research problem was first defined, and then the search terms were chosen, i.e., the keywords, and combinations using the Boolean operators "AND" and "OR." Afterwards, the search period was defined.

The PRISMA 2020 flowchart methodology (Recommended Reporting Items for Systematic Reviews and Meta-Analyzes) [13] was therefore adopted, covering the identification, selection, and inclusion of articles. The journal articles were identified by searching the following databases:

- Portal de Periódicos Capes, on 10/16/2023, with the search terms Risk management AND System dynamics AND (water supply or water management); on 11/29/2023, with the terms risk management AND system dynamics AND (water supply or water management) AND stakeholder, the search was during the period 2019 to 2023;
- Web of Science on 2/01/2024, risk management AND system dynamics AND stakeholder AND

(water supply or water management), the search was during the period 2019 to 2023;
- Science Direct, on 12/10/2023, a random search on the website was conducted, using the search terms risk management AND system dynamics AND (water supply or water management), the search was during the period 2019 to 2023;
- Google Scholar on 05/31/2024, random search on the website using the search terms risk management AND system dynamics AND (water supply or water management), the search was during the period 2019 to 2023.

The filters used in the searches were: journal articles; published from 2019 onward; in English; and peer-reviewed. The search for articles based on keywords was complemented by a snowball sampling strategy, in which additional relevant articles were found in a reference list of articles already included in the sample. Duplicate papers and review articles were excluded.

In the selection stage, the titles, keywords, and abstracts of each of the identified articles were read and analyzed, resulting in an initial selection of scientific articles which were downloaded for reading. The following exclusion criteria were applied:
- Works which did not meet high-quality academic standards, with an impact factor exceeding criteria 1;
- Works which did not involve applications of a SD modeling approach with qualitative and/or quantitative steps; and Works which were not peer-reviewed by a journal.

The Semantic-Analysis Expert (My-SAE) software was used to analyze the most mentioned keywords, journals by year of publication, and the list of journals in which the articles were published.

Results and Discussion

A total of 552 articles were obtained, including relevant publications. Only articles in English, peer-reviewed, and searched in the following search engines: Periódicos Capes, accessed on 10/16/2023, resulting in 405 articles, and on 11/29/2023, resulting in 27 articles; Web of Science, accessed on 02/01/2024, with 101 articles obtained. This research was complemented by a search in Science Direct, with 18 articles manually selected, and Google Scholar, with the selection of 1 article. The flow chart (Figure 1) represents the article search process adopted and adapted according to the PRISMA 2020 guidelines.

Forty (40) relevant articles were included in the systematic review. There was an increase in the number of publications between 2019 and 2023, from 8 publications in 2019 to 9 in 2021; in 2022 there was a further drop; and in 2023, 11 articles were published (Figure 2). This demonstrates the scientific community's interest in this topic.

The 10 keywords or search terms most present in the articles investigated are shown in Figure 4: system dynamics (31.7%), climate change (12.2%) and water resources (9.8%). The terms "water management" and "participatory modeling" reached 7.3%, the same percentage as most of the keywords present in the articles, and the latter represents the presence of modeling which includes stakeholder participation.

Figure 1. Flowchart of the article search process, adapted according to the PRISMA 2020 guidelines

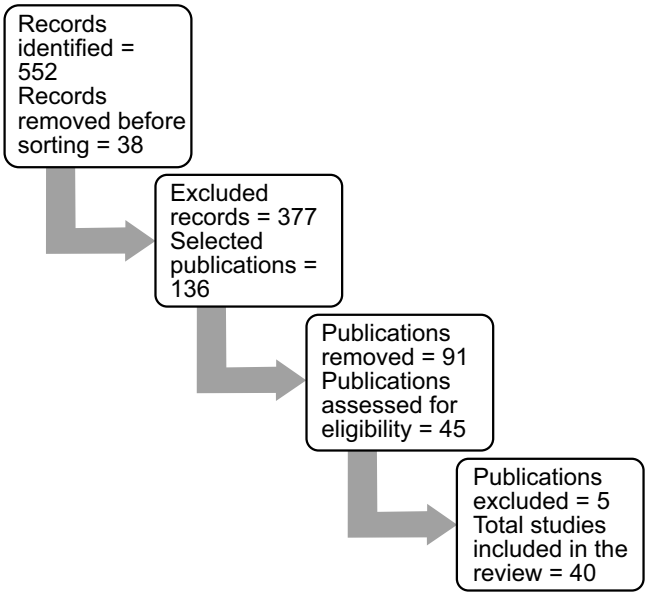


Figure 2. Number of articles per year of publication.

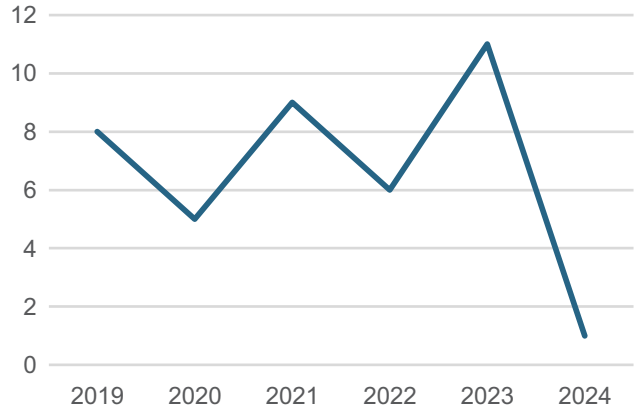
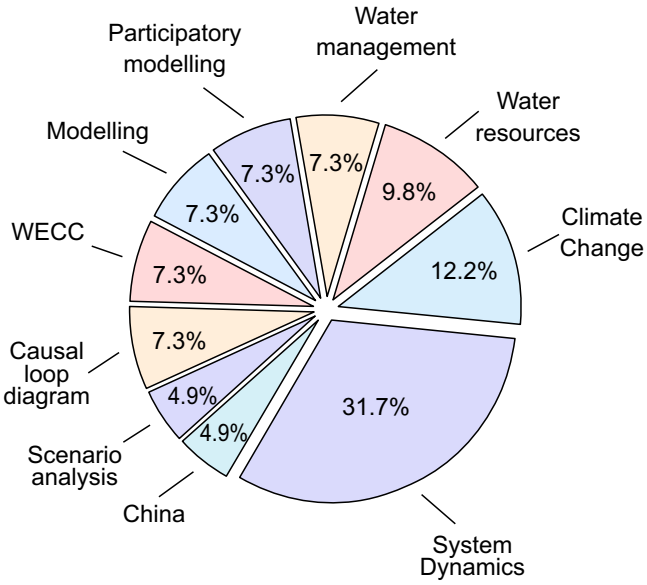


Figure 3. Keywords.



The term "causal loop diagram" also stands out, with 7.3%, revealing the use of qualitative modeling. The term "scenario analysis" appears in 4.9%, highlighting modeling which adopts scenario analysis, and "China" also in 4.9%, revealing that many models were developed for the reality of the Chinese country. The words "risk" and "risk management" do not appear among the most mentioned keywords, which may indicate a gap in the studies (Figure 3).

The analyzed studies in this article developed SD models in the field of water resources. As indicated in Table 1, 15% of the studies are purely qualitative and present the Causal Loop Diagrams (CLD); 40% develop quantitative analysis with the Stock and Flow Diagram (SFD); 45% of the studies developed qualitative and quantitative modeling, has developed CLDs and the SFD, defining the corresponding equations, which allows the tools of the system dynamics approach to be explored more widely.

SD models integrated with other modeling tools were identified in 47% of quantitative modeling, which may indicate a way to deal with the possible limitations found when using the SD model alone. Approximately 53% of the studies were carried out in Asian countries, particularly China.

The studies that analyzed modeling using subsystems represented 60% of the total, which may be associated with the complexity of the case studies. Scenario analysis was adopted in around 85% of the quantitative studies. Around 91% adopted some method to test the models (validation, calibration, and or sensitivity analysis tests), revealing the importance of testing the model before performing the simulations, ensuring greater reliability in the results. The judgment of experts and stakeholders was also found in model testing.

The most used software in the studies was Vensim, even for calibrating, validating, and analyzing the sensitivity of the models. Approximately 68% of the quantitative modeling indicated the unit and time horizon of the simulations, with the majority of the time units used being the annual, and of these models, half were carried out over a long-term horizon of more than 30 years.

Few articles have dealt with water supply companies, and only one article has stated that it had one of these companies as a case study, which may indicate a gap given that organizations also represent systems which have exogenous and endogenous complexities at different levels.

The subjects covered in studies dealing with sanitation companies included water supply failures and emergency measures to address the problem; the Life Cycle Assessment (LCA); Water resource management policies; leaks in the distribution network or real losses and apparent

Table 1. Studies analyzed.

Causal Loop Diagrams – CLD (15%)	Stock and Flow Diagram – SFD (40%)
Mai and colleagues (2019) [14]; Tantoh; Mckay (2021) [15]; Bross; Krause (2021) [16]; Sundar; Narayan; Scholten (2022) [17]; Ntajal and colleagues (2022) [18]; Asif and colleagues (2023) [19].	Hassanzadeh and colleagues (2019) [20]; Tsai and colleagues (2019) [21]; Pagano and colleagues (2019) [22]; Rubio-Martin and colleagues (2020) [9]; Giordano and colleagues (2021) [23]; Youzhi; Alexander; Ping (2021) [24]; Ignjatović and colleagues (2021) [25]; Hu and colleagues (2021) [26]; Lindqvist and colleagues (2022) [27]; Wang and colleagues (2022) [11]; Yuan and colleagues (2022) [28]; Dai and colleagues (2022) [29]; Shiu and colleagues (2023) [30]; Cotera et al. (2023) [31]; Tang and colleagues (2023) [32]; Wang; Fu (2023) [33].
CLD AND SFD (45%)	
Ahmadi; Zarghami (2019) [34]; Barati; Azadi; Scheffran (2019) [35]; Malisa; Schwella; Batinge (2019) [36]; Correia; Oliveira; Sahin (2019) [37]; Babamiri and colleagues (2020) [38]; Xu; Yao: Chen (2020) [39]; Gallagher and colleagues (2020) [40]; Elsayed and colleagues (2020) [41]; Pluchinotta and colleagues (2021) [7]; Shen and colleagues (2021) [42]; Mazzoleni and colleagues (2021) [43]; Urban; Nakada; De Lima (2023) [44]; Zuluaga-Guerra and colleagues (2023) [45]; Wang; Dong; Sušnik (2023) [46]; Barati; Pour; Sardooei (2023) [47]; Shahsavari-Pour and colleagues (2023) [48]; Zhou and colleagues (2023) [49]; Kotir and colleagues (2024) [50].	

losses; operating costs and revenues; water production, distribution, and treatment activities.

We found that 30% of the analyzed studies understand the importance of involving stakeholders and experts in SD models, either directly or indirectly. Some of the authors use the term "participatory modeling" and emphasize the benefits of this type of method, as well as the challenges and difficulties faced. Among the benefits are the possibility of integrating stakeholder knowledge into the modeling process, greater understanding, and engagement of strategic stakeholders with the modeling results for decision making.

The techniques used to extract knowledge from stakeholders involved workshops, surveys, semi-structured interviews, and focus groups. The use of social network analysis and the identification of new agents using the snowball technique were mentioned in the papers.

Studies dealing with risks in modeling accounted for 20% of the total and had as their scope of analysis the operation of dams, reservoir systems, annual and monthly changes in water supply at the basin scale, water transfer projects and Water Environment Carrying Capacity (WECC). Only 3 studies explicitly used risks as variables in CLDs and SFD models, which may represent a gap.

Overall, the risks arising from climate change and socio-economic development were analyzed in particular. These risks, alone or together, can affect the supply of water from river basins, underground springs and, in turn, affect urban and rural water supply, with consequences for the service provided by water supply companies.

However, no studies were identified in the selected sample that developed models to deal with these and other risks at the organizational level. In some studies, risks that could affect sanitation companies were mentioned, such as operational and maintenance risks, i.e., those associated with infrastructure resilience.

Companies which provide water supply services carry out water catchment, treatment,

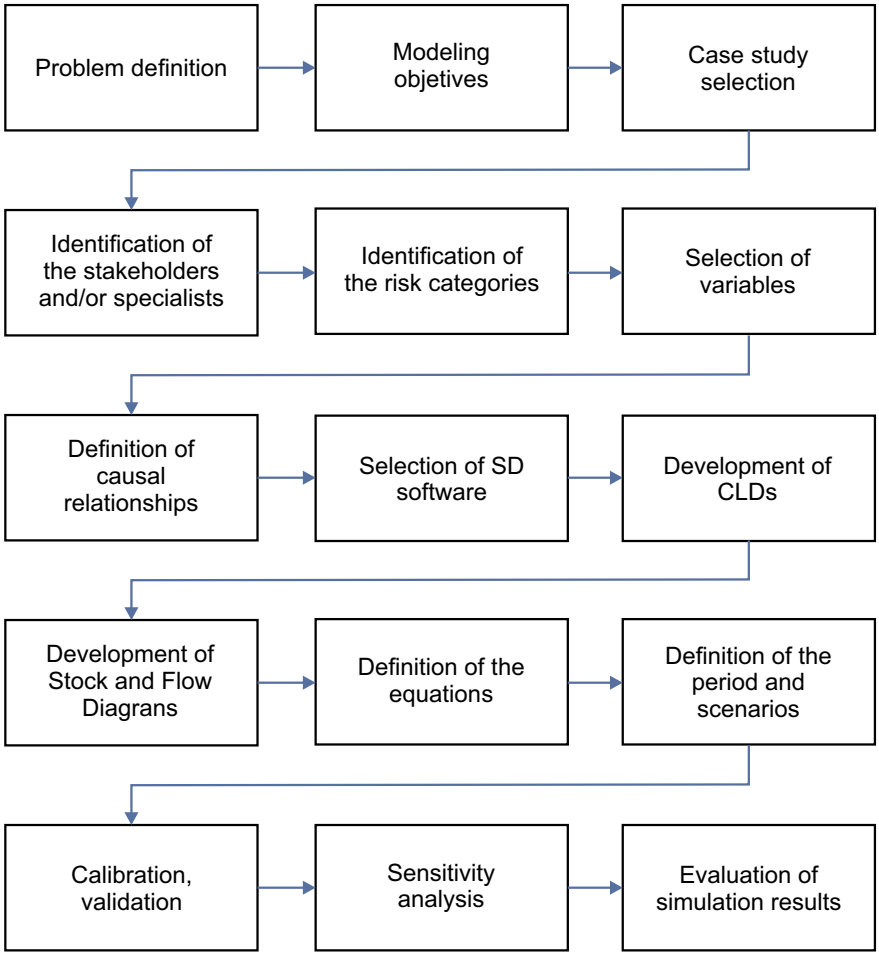
and distribution activities to guarantee a supply of drinking water that meets the demands of the population, economic sectors, and the public sector. As such, their actions involve the operation of infrastructure such as dams, water treatment plants, water distribution networks, reservoirs, and others, as well as commercial activities in direct contact with end users. They must meet the targets of SDG 6, as well as the applicable legislation.

The environment in which these companies operate includes external challenges such as climate change, water pollution, poor land use and planning, which can affect surface and underground water sources; changes in the legal and regulatory environment, and others. And internal challenges such as operational issues, such as deteriorated infrastructure, which increases leaks in distribution networks; financial and economic issues such as setting tariffs, that cover operational and administrative costs and do not harm consumers; deciding on new investments in infrastructure or new technologies; optimizing the water balance, among others.

This indicates that they operate in complex environments marked by uncertainties, making it necessary to carry out an adequate risk management process with the view of achieving organizational objectives within the scope of their governance actions.

As such, SD represents a promising approach to dealing with these issues. Based on the results obtained in this work, a framework was proposed to develop a SD model for risk management in water supply companies, whether or not they already adopt risk management. The framework is detailed in Figure 4.

Figure 4. Framework for developing SD modeling for risk management in water utilities.



Some of the limitations of the scope of this work include the time available for research, the number of researchers involved, and the number of databases of articles accessed. The use of the search terms and Booleans chosen may also have restricted the selection of other articles.

For future research, we suggest expanding the search database and using other search terms, as well as selecting articles in other languages.

Conclusion

From the results of this work, it can be concluded that water resource management presents major challenges and complexities that cover different levels, including environmental, climate, economic, social, and hydrological factors.

Thus, studies in this area cover issues associated with freshwater sources, whether from rivers, river basins, or underground springs, such as the impoundment of the water in dams and reservoirs and its management, water imports, and issues that cross borders between countries and regions. They also involve the challenges faced in the operation of sustainable urban water systems, which cover the water catchment, treatment, and distribution processes to guarantee universal access to drinking water for the various users, as well as defining the price of the use of the resource.

In the management of water resources, the studies indicate actions on the demand side, such as raising awareness of the rational use of water and the use of tariffs to restrict the increase in consumption, and on the supply side, actions such as the possibility of exploring alternative sources of water to meet the growing demand, including the use of wastewater treatment technologies, rainwater harvesting, desalination, and others.

The challenges posed by climate change, especially socioeconomic and other factors, make the management of water resources even more complex. For companies operating water supply systems, the challenges are many, and they operate in environments marked by uncertainty and complexity. This requires an appropriate risk management process.

To address this complexity, the common point in the selected studies was the use of the system dynamics approach in the management of water resources, alone or in conjunction with other approaches. There was a tendency to develop participatory modeling with the participation of stakeholders and experts.

In the sample of analyzed articles, few studies dealt with risks or risk management in the context of water resources based on system dynamics. The identified articles focused on the operation of dams and reservoir systems, annual and monthly changes in water supply at the basin scale, water transfer projects, WECC, and none assessed risks at the organizational level in companies operating water supply systems. This may reveal a gap. To this end, this paper presents a proposal for a model based on system dynamics to address risk management from the perspective of water supply companies.

The scope of this study was limited, which may have excluded relevant studies in the analyzed period from the analysis. As a proposal for future work, we suggest extending the analysis period and the search bases and reviewing the filters used.

References

1. Wang X, Zhang J, Liu J, Wang G, He R, Elmahdi A, et al. Water resources planning and management based on system dynamics: a case study of Yulin city. Environment, Development and Sustainability. 2010 Sep 15;13(2):331–51.
2. Davies EGR, Simonovic SP. Global water resources modeling with an integrated model of the social–economic–environmental system. Advances in Water Resources. 2011 Jun;34(6):684–700.
3. United Nations. The Sustainable Development Goals Report 2022 [Internet]. unstats.un.org. United Nations; 2022. Available from: https://unstats.un.org/sdgs/report/2022/.
4. Pereira MA, Marques RC. Sustainable water and sanitation for all: Are we there yet? Water Research. 2021 Dec;207:117765.
5. World Economic Forum - Home [Internet]. Weforum.org.2024. Available from: https://www3.weforum.org/docs/WEF_The_Global_ Risks_Report_2024.
6. Haimes YY. On the Complex Definition of Risk: A Systems-Based Approach. Risk Analysis. 2009 Dec;29(12):1647–54.

7. Pluchinotta I, Pagano A, Vilcan T, Ahilan S, Kapetas L, Maskrey S, et al. A participatory system dynamics model to investigate sustainable urban water management in Ebbsfleet Garden City. Sustainable Cities and Society. 2021 Apr;67:102709.
8. Phan TD, Bertone E, Stewart RA. Critical review of system dynamics modelling applications for water resources planning and management. Cleaner Environmental Systems. 2021 Jun;2:100031.
9. Rubio-Martin A, Pulido-Velazquez M, Macian- Sorribes H, Garcia-Prats A. System Dynamics Modeling for Supporting Drought-Oriented Management of the Jucar River System, Spain. Water. 2020 May 15;12(5):1407.
10. Brugha R, Varvasovszky Z. Stakeholder analysis: a review. Health Policy and Planning [Internet]. 2000 Sep 1;15(3):239–46. Available from: https://academic.oup.com/heapol/article/15/3/239/57 3296.
11. Wang F, Liu B, Li H, He Y. Research on real-time risk monitoring model along the water transfer project: a case study in China. Water Supply. 2022 Feb 25;22(4):4477–88.
12. Jesson J, Matheson L, Lacey FM. Doing Your Literature Review: Traditional and systematic techniques. SAGE; 2011.
13. Page M, Tetzlaff J, Moher D. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. Value in Health. 2021 May;23(10):S312–3.
14. Mai T, Mushtaq S, Loch A, Reardon-Smith K, An-Vo DA. A systems thinking approach to water trade: Finding leverage for sustainable development. Land Use Policy. 2019 Mar;82:595–608.
15. Tantoh HB, McKay TJM. Assessing community- based water management and governance systems in North-West Cameroon using a Cultural Theory and Systems Approach. Journal of Cleaner Production. 2021 Mar;290:125804.
16. Bross L, Krause S. Will There Be Enough Water? A System Dynamics Model to Investigate the Effective Use of Limited Resources for Emergency Water Supply. Systems. 2021 Jan 8;9(1):2.
17. Sundar Navamany CG, Narayan AS, Scholten L. There is no environmental health without public health: exploring the links between sanitation and waterbody health in Bengaluru, India. Environment and Urbanization. 2022 Apr;34(1):76–98.
18. Ntajal J, Höllermann B, Falkenberg T, Kistemann T, Evers M. Water and Health Nexus—Land Use Dynamics, Flooding, and Water-Borne Diseases in the Odaw River Basin, Ghana. Water [Internet]. 2022 Jan 1;14(3):461. Available from: https://www.mdpi.com/2073-4441/14/3/461/htm.
19. Asif M, Inam A, Adamowski J, Shoaib M, Tariq H, Ahmad S, et al. Development of methods for the simplification of complex group built causal loop diagrams: A case study of the Rechna doab. Ecological Modelling. 2023 Feb;476:110192.
20. Hassanzadeh E, Strickert G, Morales-Marin L, Noble B, Baulch H, Shupena-Soulodre E, et al. A framework for engaging stakeholders in water quality modeling and management: Application to the Qu'Appelle River Basin, Canada. Journal of Environmental Management. 2019 Feb;231:1117– 26.
21. Tsai WP, Cheng CL, Uen TS, Zhou Y, Chang FJ. Drought mitigation under urbanization through an intelligent water allocation system. Agricultural Water Management [Internet]. 2019 Mar;213:87–96.Available from:https://www.sciencedirect.com/science/article/pii/S0 378377418315695.
22. Pagano A, Pluchinotta I, Pengal P, Cokan B, Giordano R. Engaging stakeholders in the assessment of NBS effectiveness in flood risk reduction: A participatory System Dynamics Model for benefits and co-benefits evaluation. Science of The Total Environment. 2019 Nov;690:543–55.
23. Giordano R, María Máñez Costa, Pagano A, Rodríguez B, Zorrilla-Miras P, Gomez E, et al. Combining social network analysis and agent-based model for enabling nature-based solution implementation: The case of Medina del Campo (Spain). Science of The Total Environment. 2021 Dec 1;801:149734–4.
24. Youzhi W, Alexander F, Ping G. A model integrating the system dynamic model with the risk based two-stage stochastic robust programming model for agricultural-ecological water resources management. Stochastic Environmental Research and Risk Assessment. 2021 Jan 27;
25. Ignjatović L, Stojković M, Ivetić D, Milašinović M, Milivojević N. Quantifying Multi-Parameter Dynamic Resilience for Complex Reservoir Systems Using Failure Simulations: Case Study of the Pirot Reservoir System. Water. 2021 Nov 9;13(22):3157.
26. Hu G, Zeng W, Yao R, Xie Y, Liang S. An integrated assessment system for the carrying capacity of the water environment based on system dynamics. Journal of Environmental Management. 2021 Oct;295:113045.
27. Lindqvist AN, Fornell R, Prade T, Khalil S, Tufvesson L, Kopainsky B. Impacts of future climate on local water supply and demand – A socio- hydrological case study in the Nordic region. Journal of Hydrology Regional Studies. 2022 Mar 30;41:101066–6.
28. Yuan L, He W, Degefu DM, Kong Y, Wu X, Xu S, et al. Elucidating competing strategic behaviors using prospect theory, system dynamics, and evolutionary game: a case of transjurisdictional water pollution problem in China. Environmental science and pollution research international [Internet]. 2022 Mar 1;29(14):20829–43. Available from: https://eds.s.ebscohost.com/eds/detail/detail?vid=2&sid=43a749c9-b9e7-4a1d-8861- 642f50a0095e%40redis&bdata=JnNpdGU9ZWRzL WxpdmU%3d.

29. Dai D, Sun M, Lv X, Hu J, Zhang H, Xu X, et al. Comprehensive assessment of the water environment carrying capacity based on the spatial system dynamics model, a case study of Yongding River Basin in North China. Journal of Cleaner Production. 2022 Apr;344:131137.
30. Shiu HY, Lee M, Lin ZE, Chiueh PT. Dynamic life cycle assessment for water treatment implications. Science of The Total Environment [Internet]. 2023 Feb 20;860:160224. Available from: https://www.sciencedirect.com/science/article/abs/pii/S0048969722073247.
31. Valencia Cotera R, Guillaumot L, Sahu RK, Nam C, Lierhammer L, Máñez Costa M. An assessment of water management measures for climate change adaptation of agriculture in Seewinkel. Science of The Total Environment [Internet]. 2023 Aug 10;885:163906. Available from: https://www.sciencedirect.com/science/article/pii/S0 048969723025275.
32. Tang J, Song P, Hu X, Chen C, Wei B, Zhao S. Coupled effects of land use and climate change on water supply in SSP–RCP scenarios: A case study of the Ganjiang River Basin, China. Ecological Indicators [Internet]. 2023 Aug 1;154:110745. Available from:https://www.sciencedirect.com/science/article/pii/S1 470160X23008877.
33. Wang Z, Fu X. Scheme simulation and predictive analysis of water environment carrying capacity in Shanxi Province based on system dynamics and DPSIR model. Ecological Indicators. 2023 Aug 26;154:110862–2.
34. Ahmadi MH, Zarghami M. Should water supply for megacities depend on outside resources? A Monte-Carlo system dynamics simulation for Shiraz, Iran. Sustainable Cities and Society. 2019 Jan;44:163–70.
35. Barati AA, Azadi H, Scheffran J. A system dynamics model of smart groundwater governance. Agricultural Water Management. 2019 Jul;221:502– 18.
36. Malisa R, Schwella E, Batinge B. Augmenting Water Supplies Through Urban Wastewater Recycling (March 2019). IEEE Systems Journal. 2020 Mar;14(1):1523–30.
37. Correia de Araujo W, Oliveira Esquerre KP, Sahin O. Building a System Dynamics Model to Support Water Management: A Case Study of the Semiarid Region in the Brazilian Northeast. Water [Internet]. 2019 Dec 1;11(12):2513. Available from: https://www.mdpi.com/2073- 4441/11/12/2513/htm
38. Babamiri AS, Pishvaee MS, Mirzamohammadi S. The analysis of financially sustainable management strategies of urban water distribution network under increasing block tariff structure: A system dynamics approach. Sustainable Cities and Society. 2020 Sep;60:102193.
39. Xu Z, Yao L, Chen X. Urban water supply system optimization and planning: Bi-objective optimization and system dynamics methods. Computers & Industrial Engineering. 2020 Apr;142:106373.
40. Gallagher L, Kopainsky B, Bassi A, Betancourt A, Buth C, Chan P, et al. Supporting stakeholders to anticipate and respond to risks in a Mekong River water-energy-food nexus. Ecology and Society [Internet]. 2020 Dec 2;25(4). Available from: https://www.ecologyandsociety.org/vol25/iss4/art29/
41. Elsayed H, Djordjević S, Savić DA, Tsoukalas I, Makropoulos C. The Nile Water-Food-Energy Nexus under Uncertainty: Impacts of the Grand Ethiopian Renaissance Dam. Journal of Water Resources Planning and Management. 2020 Nov;146(11):04020085.
42. Shen G, Lu Y, Zhang S, Xiang Y, Sheng J, Fu J, et al. Risk dynamics modeling of reservoir dam break for safety control in the emergency response process. Water Supply. 2021 Jan 4;21(3):1356–71.
43. Mazzoleni M, Odongo VO, Mondino E, Di Baldassarre G. Water management, hydrological extremes, and society: modeling interactions and phenomena. Ecology and Society. 2021;26(4).
44. Urban RC, Nakada LYK, Isaac R de L. A system dynamics approach for large-scale water treatment plant sludge management: A case study in Brazil. Journal of Cleaner Production [Internet]. 2023 Sep 20;419:138105. Available from: https://www.sciencedirect.com/science/article/pii/S0 959652623022631
45. Zuluaga-Guerra PA, Martinez-Fernandez J, Esteve-Selma MA, Dell'Angelo J. A socio-ecological model of the Segura River basin, Spain. Ecological Modelling. 2023 Apr;478:110284.
46. Wang X, Dong Z, Sušnik J. System dynamics modelling to simulate regional water-energy-food nexus combined with the society-economy- environment system in Hunan Province, China. Science of The Total Environment [Internet]. 2023 Mar 10;863:160993. Available from: https://www.sciencedirect.com/science/article/abs/pii/S0048969722080962
47. Ali Akbar Barati, Milad Dehghani Pour, Mohsen Adeli Sardooei. Water crisis in Iran: A system dynamics approach on water, energy, food, land and climate (WEFLC) nexus. 2023 Jul 1;882:163549–9.
48. Shahsavari-Pour N, Bahador S, Heydari A, Fekih A. Water Shortage Simulation Using a System Dynamics Approach: A Case Study of the Rafsanjan City. Sustainability. 2023 Apr 4;15(7):6225.
49. Zhou Y, Lu N, Hu H, Fu B. Water resource security assessment and prediction in a changing natural and social environment: Case study of the Yanhe Watershed, China. 2023 Oct 1;154:110594–4.
50. Kotir JH, Jagustovic R, Papachristos G, Zougmore RB, Kessler A, Reynolds M, et al. Field experiences and lessons learned from applying participatory system dynamics modelling to sustainable water and agri-food systems. Journal of cleaner production. 2024 Jan 1;434:140042–2.

Attitude Control Systems for Nanosatellites: A Systematic Review

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As technology advances, electronic components and devices get miniaturized, nanosatellites can hold denser payloads with more sensors, requiring attitude control to point precisely both sensors and antenna to send back to ground stations on Earth the acquired data. Such important techniques have been researched since the 90's to develop efficient technology due to lack of space, available energy to the tasks and their criticality, many techniques and designs have been developed and tested since then. In this review, using PRISMA methodology, some of this research will be presented focusing on the actual more used ones, like reaction wheels, magnetorquers and other perspectives as attitude control by shifting masses. A summary of findings was constructed to highlight these review points, and a discussion was made right after about the possible gaps. The presented techniques show some flaws when used as the only control device separately but have the tendency to minimize it when combined. However, using both methods requires more battery usage, processing and raises the nanosatellite's costs, since these dedicated actuators are highly expensive. In the other hand, experimental techniques, based in moving mass actuators presented promising results in terms of energy saving, precision, time to convergence, but requires more intricate calculations and a refined control due its non-linearities intrinsic to the systems construction and a single physical prototype have been displayed until the writing of this review. In conclusion, there's a clear preference for applying reaction wheels and magnetorquers together to Attitude Determination and Control Systems (ADCS), but its common problems could be solved by using another technique such as moving mass control, a field where still have great opportunities to innovative, equally efficient techniques and the possibility of pioneering the construction of a physical functional prototype, even with its own peculiarities.
Keywords: Attitude Control. Nanosatellites. Aerospace Engineering. Literature Review. CubeSat.

In 2025 there's at least 790 CubeSats launches predicted [1], and technologies aimed at aerospace engineering became a major importance subject in the international scenario recently.

One of the subjects of interest is the development of devices called nanosatellites for exploration and monitoring of Low Earth Orbit (LEO) and the Very Low Earth Orbit (VLEO) because of its overall of cost-effectiveness since the imagery are improved, payloads, antennas, transmission power are drastically reduced if compared with common high altitude satellites and the launcher needs less power and fuel to execute the missions [2]. On the other hand, low altitude means denser air and consequently more perturbations (Fortescue and Stark apud [2]) that need to be dealt with by control systems to damp the oscillations and keep the cubic satellite stable.

The most used devices to integrate attitude control systems in nanosatellites are magnetorquers and reaction wheels (H. Polat and colleagues apud [1]), but at the same time they are still expensive devices when thinking about the allocated budget to researchers, students and minor institutions [3], especially in Brazil. Even in countries where there is more investment, the cost of these devices is still a concern to universities and laboratories, leading to research to develop solutions such as low-cost reaction wheels [3] or new concepts as moving mass actuators to control nanosatellites [4,5].

In countries with low tradition and investment in technology research and low levels of industrialization the development of devices based in marginal technologies can, besides the cost reduction, put it in an advantageous situation of dispute its place on the subject's technological vanguard by owning not only the intellectual property, but also the know-how to deal with the

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new technology, creating alternative paths to the goal.

The bigger challenges about moving mass control are connected to strong nonlinear behavior; the application of advanced nonlinear control techniques, such as Lyapunov stability theory [4]; the need of physical space to operate the moving parts; and positioning of the parts in must to be in trivial positions along the vehicle [6].

In this paper, the aim is to compile the last ten years contributions in the area of attitude control systems for nanosatellites, that fits the systematic review criteria, with emphasis in shifting mass. By means of this review, several documents about the current techniques and technologies already on the market are analyzed in terms of research and innovative interest in new studies.

This document is segmented into the following content: Section 2 describes the systematic review approach applied. Section 3 presents the results obtained and a discussion about the methods and technologies used in attitude control systems. Section 4 presents the conclusions and future works.

Materials and Methods

For this review, the literature systematic process referred as Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) was adopted [7]. The queried databases were: ScienceDirect, Google Scholar, CAPES Periodic and IEEE Xplore, used as primary research sources, all known for their reliability and large number of relevant documents, however the adopted search string returned no results in the IEEE Xplore case.

The keywords used were Attitude Control, Shifting mass, CubeSats, Nanosatellites, Unbalanced and Center of mass, in this context, the constructed terms for the research using the connectives and, or and quotes were ("Shifting mass" OR (("moveable" OR "changeable" OR "unbalanced") AND "center of mass")) AND ("Attitude control" OR "Modeling") AND ("CubeSats" OR "nanosatellites"), used in the search box exactly this way for all the sources. 176 documents were found in the period from 2014 to 2024, among them articles, thesis, dissertations, papers and a survey. The citations archives were uploaded to Rayyan, an AI systematic review management platform. From this tool, 18 duplicates were detected and excluded. By reading the 157 remaining titles and abstracts, 139 were excluded because of their relevance and connection to the topic and among the 18 remaining, 5 required premium login to access the content. Finally 13 were selected for full reading based on their title and abstract's information. The Figure 1 resumes the process and the number of documents excluded and remaining after each step. The following link redirects the reader to a PRISMA Checklist 2009 version: [https://drive.google.com/file/d/10BQbPEs77oxAV2iIpcG3O_-ZXXVZe_GZ/view].

Results and Discussion

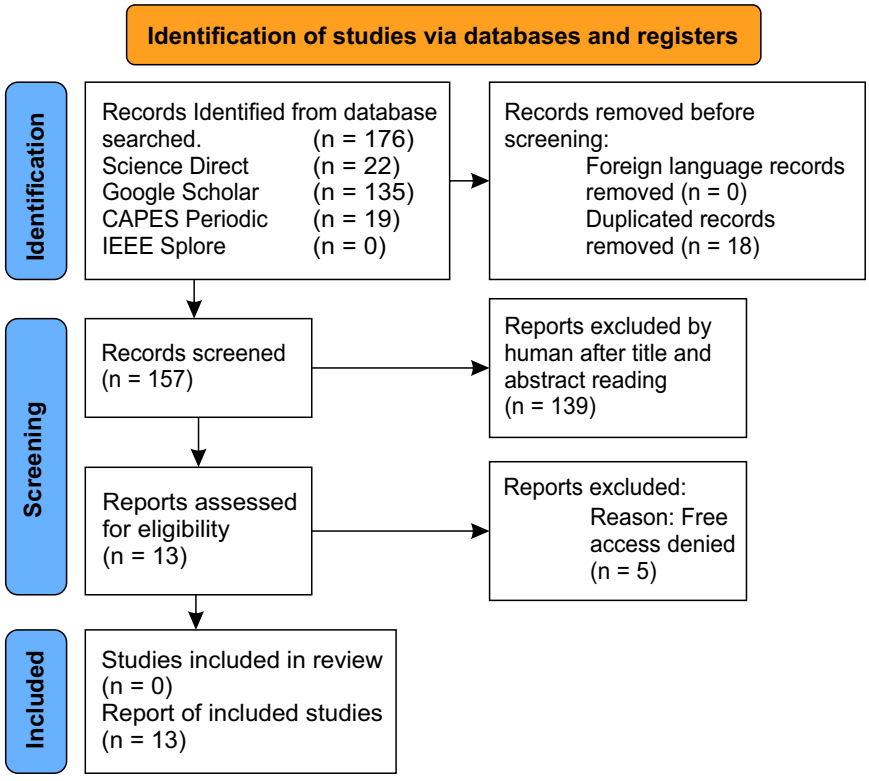
The quantity of published documents about CubeSats has had an ascendent tendency line since 2014, even reaching its lower point in 2022, as observed in Figure 2.

An important point to note during this period is the change in terms used in research titles. Initially, the term "nanosatellite" was more used, but it led to less reach due to a more specific concept. After the term was back to "CubeSat" and, consequently, has more reach in research. Currently, the term "spacecraft" has gained prominence due to its more generic scope. Another thing to acknowledge is that 2022 the world felt the remaining problems caused by the COVID-19 Pandemic. These impacts closed laboratories, shortened the research budget to some entities which led to, in some sectors, delays in publications, unemployment and the premature ending of some research. All these factors combined may explain the phenomenon.

Figure 3 illustrates in Mundi-Map how these documents are distributed in the world. From the most relevant papers, it is clear the polarization

of this new space race between the United States and China, with six and four documents included, respectively. Besides, this graphic presents the necessity of more debate, publications and incentives to Brazil to dispute space in this new scenario to avoid too much technological dependence. The development of research in this area of knowledge in Brazil still needs to grow in numbers and especially in innovative ways. In this search, for example, among all 157 not duplicated documents only 2 articles were from Brazil, which represents 1.27%. Table 1 summarizes all documents obtained in this research, chronologically displayed, and the summary of findings.

Figure 1. PRISMA Diagram for attitude control system review.



Source: Adapted from Moher and colleagues [7].

Figure 2. Studies found in research.

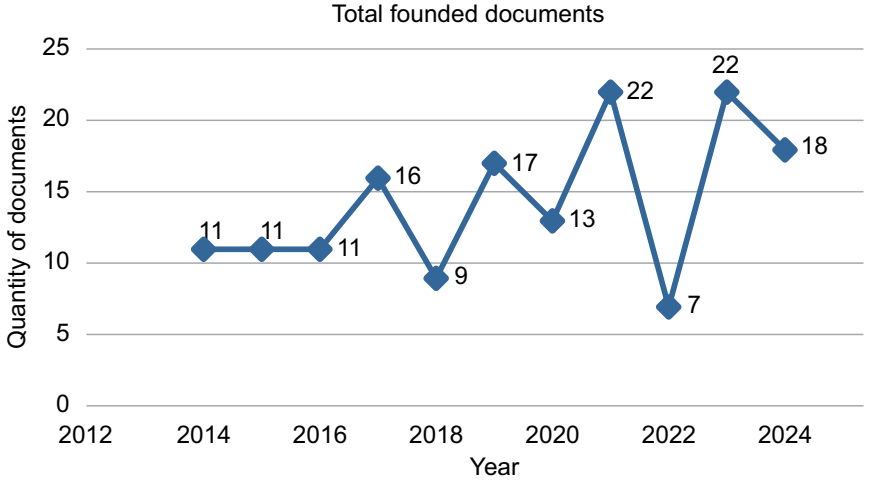
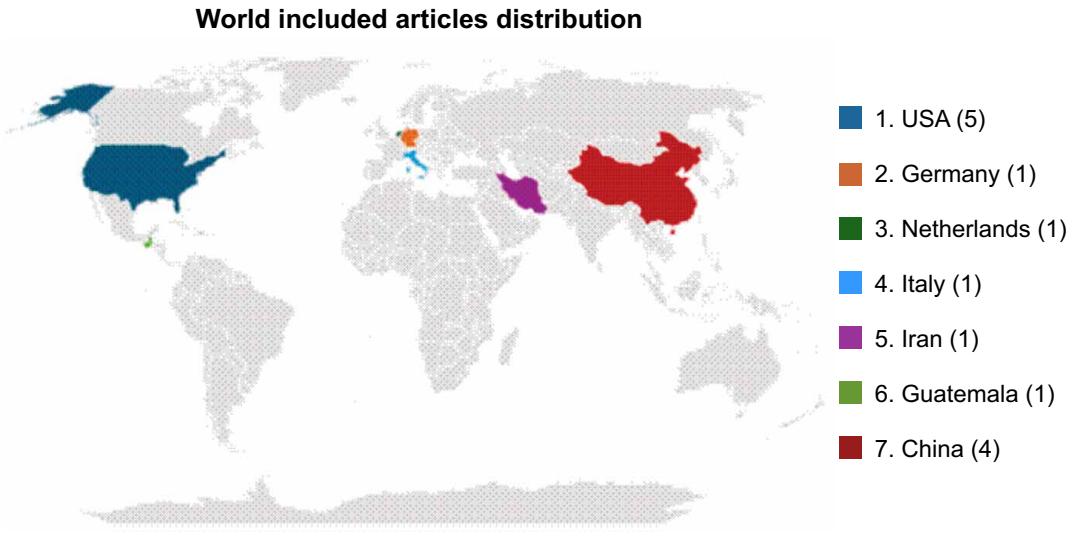


Figure 3. World included articles distribution.



Chesi [4] presented in his work a concept of attitude control of nanosatellites using shifting masses by creating distance between the center of pressure and center of mass to use the disturbance force of atmospheric drag as control force. Although mathematically this technique is possible it was proved using only math simulation and there's no visual concept of this system or how it would be if constructed. Even only published in 2017, in 2015 Shaik's [12] work presented a final assembly CubeSat using moving mass technique, but his spherical prototype had 198 mm diameter which is almost double far from the dimensions and shape specification proposed by the previous research cited, turning it impractical for conventional launchers.

Virgili-Llop and colleagues [2] studies proposed a 3U CubeSat concept with the shape of real devices in CAD, but there's no information if it was manufactured. Even with co-authors in common, Chesi and colleagues [11] kept the work in the theoretical field and the same hypothesis from his PhD thesis were maintained to facilitate the calculations and applications of the theorems. This increased interest about moving mass encouraged

Li and colleagues [6] to conduct a survey about it. They concluded that despite the shifting mass method showing great advantages most works in this field stayed at theoretical design and simulations because it is non-linear behavior and the mechanical engineering practical difficulties.

This survey paved the way to Qian and colleagues [5] research, now with Li as second author. They also presented a theoretical model without engineering implementation. Moreover, they just cited the use of magnetorquers to compose the system but did not present more modelling or detail on it.

Chait and colleagues [8] also pointed out that reaction wheels and magnetorquers are well-known and modelled since 2015 which means it is a consolidated technology and there's few contributions to be made, no other than design and manufacturing to lower budget. In sequence, Curatolo [1] integrated reaction wheel and magnetorquer technologies in CubeSat considering in research three different control methods. However, this configuration lacks innovation in the aerospace market. Not by chance, Lee and colleagues [3] were able to design, manufacture and assemble a reaction wheel technology device based on their authorial motor concept. Reaction wheels are shown as a well-established product in a way that research in this field leads, most of the time, to budget reductions.

Table 1. Articles' compilation.

Reference	Objective	Attitude Control Method	Summary of Findings
[4]	Develop a novel attitude control system through shifting masses.	Shifting Mass	Technique based on shifting masses to variate aerodynamic torque. Use of Lyapunov stability theory.
[8]	MATLAB/Simulink application to test CubeSats hardware in a laboratory.	Reaction Wheels + Magnetorquers	Simulated environment in MATLAB/Simulink to test hardware-in-loop.Actuators, perturbations and physics modelled.
[2]	Shifting masses to reject aerodynamic disturbances and stabilize the spacecraft's attitude.	Shifting Mass	Departed from Chesi's (2015 [6]). Disturbances' mitigation to stabilize CubeSats Computer Aided Design (CAD) of a 3U CubeSat.
[9]	Verify and validate the possibility to control the attitude of CubeSat with magnetic rods as actuators only.	Magnetorquers	Tested the system using MATLAB/Simulink and hardware in loop to stabilize spin in satellites.
[10]	Development of a CubeSat to Earth observation with stability and high accuracy using momentum wheels within a competitive cost.	Momentum Wheels	Tested an attitude control system with only two momentum wheels to provide to the spacecraft the capability of Earth pointing and spin stabilization in VLEO.
[11]	Attitude control to CubeSats based on center-of-mass shifting paired with reaction wheels or magnetorquers.	Shifting Mass + Reaction Wheels and Shifting Mass + Magnetorquers	Shifting mass techniques for stabilization of a spacecraft. Added a set of actuators based on conventional techniques.
[12]	Design, fabrication and modelling of a plug and play CubeSat with controllable center of mass and reaction wheels in a sphere.	Reaction Wheels + Shifting Mass	Built a floating spherical satellite designed to operate on an air bearing surface. Used reaction wheels and shifting mass to control the satellite. Detailed engineering choices.
[6]	Debates about moving mass technology and its applications in aerospace, military and naval areas and its challenges.	Shifting Mass	A survey about moving mass control technology in aerospace, military and naval areas, showing patents of its applications.
[13]	Investigate attitude stabilization using shifting mass technique in a two-dimensional plane.	Shifting Mass	Tested if it is possible to stabilize three-axis attitude moving masses with less than 10% of spacecraft's mass in two-axis.
[14]	Develop an eight-degree-freedom model of a 2U CubeSat propelled by solid rocket motors with two moving masses.	Solid Rocket Motors + Shifting Mass	Applied moving mass technique to control generated torque by thrust misalignment and fuel consumption. Developed a simulation of a 2U CubeSat within the objectives conditions.
[3]	Design, manufacture, assemble and test a 3-axis reaction wheel prototype to reduce expenses to Cal Poly CubeSat Laboratory.	Reaction Wheels	Reaction Wheels are expensive devices. Patent studies of reaction wheels. Catalog of existing products and suppliers. Designed, manufactured and assembled a 3-axis reaction wheel new device.
[1]	Develop an attitude control for CubeSat with three magnetorquers and one reaction wheel.	Reaction Wheels + Magnetorquers	Focused on numerical methods. Consider the orbit to determine the best results. Pondered three different control laws to choose and opted for the Linear Quadratic Regulator method.
[5]	Investigate a control technique based on moving masses to operate formations with CubeSats.	Shifting Mass + Magnetorquers	Proposed to create formations with moving mass technology as primary attitude control technique. Used Nash game theory to analyze the formation with two CubeSats.

Ousaloo and colleagues [9] successfully applied only magnetorquers to control attitude, but the convergence time was about 20 minutes in the experiment and the hardware is far from CubeSat's shape or size. Nonetheless this research stated that only magnetic actuators can provide more accurate results, but at a slower pace. In almost the same way, Ju [10] concluded that the momentum wheels technique, as the only control method, is not suitable for the task due to its inability to provide adequate transverse angular momentum levels, essential for the spacecraft's active attitude control.

He and colleagues [13] succeeded in applying moveable mass technology to attitude control using it in-plane, however, their control strategy has three defined steps to achieve it. Moreover, the movement around the Y-axis needs to be damped by aerodynamic drag to reach a controllable value. Similarly, years later, the study of Lu and colleagues [14] applied in-plane moving mass attitude control to thruster propelled CubeSats and although the simulations showed the feasible of this method the general hardware is completely different than the majority of launched CubeSats and, again, it stayed in theoretical field.

Conclusion

In this review was shown the actual relevance of research about attitude control for nanosatellites internationally. The debate around the optimized control laws and methods is still open [1]. Although reaction wheels and magnetorquers already became consolidated products, they keep high prices [3], and are not the only way to achieve the final goal.

Thinking in the national scenario the currency exchange and tariffs make the importation of these devices even more expensive and starting a local manufacturing to reduce these costs is years away from the reality. The alternative is research innovative technologies to detain patents and production nationally, bringing new alternatives to compete for space, both scientific and economic.

A viable option appears to be shifting mass technologies, recent research showed its possibilities and applications [5], and yet there is no established market or products pointed to them. Of course, some engineering challenges may be surpassed, especially in the non-linear control field, but that is the researcher's primary objective.

The work presented in Virgili-Llop and colleagues [2] in 2016 showed that back in the day using the simulations, CAD and devices' drawings of the era it was already feasible doing an assembly concept. In 2017, Shaik [12] proved that it is possible to use movable masses in a satisfactory way to control meant to be spacecraft smaller devices. From 2017 to now there's 8 years of advances in engineering overall and miniaturization of electronics that facilitates the development of movable mass technologies that fit in nanosatellites requirements. Not by chance, more recently, Qian and Zhang (2023) [5] applied this same technology to propose a formation control.

This whole scenario shows that even not being a consecrated technology it is still relevant and taking it out of computer simulations to more fit prototypes may create new technological paths to the subject.

References

1. Curatolo A. Development and experimental testing of nanosatellites attitude control using mixed magnetic/mechanical actuation [master's thesis]. Forlì (Italy): University of Bologna; 2021.
2. Virgili-Llop J, Polat HC, Romano M. Using shifting masses to reject aerodynamic perturbations and to maintain a stable attitude in very low earth orbit. Adv Astronaut Sci. 2016;158:2129-2148.
3. Lee AM, Leon D, Casillas CP, McCarver R. 3-axis reaction wheel system for CubeSats [senior project]. San Luis Obispo (CA): California Polytechnic State University; 2021.
4. Chesi S. Attitude control of nanosatellites using shifting masses [PhD thesis]. Santa Cruz (CA): University of California, Santa Cruz; 2015.
5. Qian Y, Li J, Zhang H. Formation control of satellites in low Earth orbit by using moving masses. Aerosp

Sci Technol. 2023;132:108073. doi:10.1016/j.ast.2022.108073.
6. Li J, Gao C, Li C, Jing W. A survey on moving mass control technology. Aerosp Sci Technol. 2018;82:594-606. doi:10.1016/j.ast.2018.09.033.
7. Moher D, Liberati A, Tetzlaff J, Altman DG, PRISMA Group. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med. 2009;6(7):e1000097. doi:10.1371/journal.pmed.1000097.
8. Chait SB, Spencer DA. Georgia Tech small satellite real-time hardware-in-the-loop simulation environment: SoftSim6D [master's project report]. Atlanta (GA): Georgia Institute of Technology; 2015.
9. Ousaloo HS, Nodeh MT, Mehrabian R. Verification of spin magnetic attitude control system using air-bearing-based attitude control simulator. Acta Astronaut. 2016;126:546-553. doi:10.1016/j.actaastro.2016.03.028.
10. Ju D. Attitude control subsystem design of the stable and highly accurate pointing Earth-imager [master's thesis]. Delft (The Netherlands): Delft University of Technology; 2017.
11. Chesi S, Gong Q, Romano M. Aerodynamic three-axis attitude stabilization of a spacecraft by center-of-mass shifting. J Guid Control Dyn. 2017;40(7):1613-1626. doi:10.2514/1.G002460.
12. Shaik FJ. Design, fabrication and modelling of three axis floating satellite simulator [thesis]. Luleå (Sweden): Luleå University of Technology; 2017.
13. He L, Chen X, Kumar KD, Sheng T, Yue C. A novel three-axis attitude stabilization method using in-plane internal mass-shifting. Aerosp Sci Technol. 2019;92:489-500. doi:10.1016/j.ast.2019.06.019.
14. Lu Z, Hu Y, Liao W, Zhang X. Modeling and attitude control of CubeSat utilizing moving mass actuators. Adv Space Res. 2021;67(1):521-530. doi:10.1016/j.asr.2020.09.027.

Variations of Architectures and Applications of Quantum Generative Adversarial Networks

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Generative Adversarial Networks (GANs) are generative models that function as a minimax game, in which a generative network and a discriminative network compete against each other with the goal of creating data that convincingly resembles the real sample. With the advent of Quantum Computing and the development of Quantum Machine Learning (QML) models, Quantum Generative Adversarial Networks (QuGANs) have been increasingly studied due to the possible advantages this new type of architecture can offer, especially regarding performance improvements, scalability, and the exploration of new applications. In this context, this study's guiding question is: how were QuGANs developed between the years 2018 and 2025? To answer this question, the general objective of this work is to conduct a systematic literature review of QuGANs during the proposed period. Using a systematic literature review as the methodological basis, articles published and available on the online platforms Lens, Scopus, and Web of Science were selected, and the Rayyan tool was employed to identify duplicate works and those that did not specifically address QuGANs. As a result, a prevalence of hybrid models was observed, in which the developed architecture integrates quantum and classical characteristics in a complementary manner. Regarding the type of application, approaches involving theoretical foundations and image generation stand out as the most common. Other application areas are also explored (chemistry and pharmaceuticals, quantum error correction, high-energy physics, experimental implementation, medical applications, cloud computing, anomaly detection, telecommunications, biometrics, finance, physics and simulations, security and cryptography, software engineering, noise in QuGANs, and survey), demonstrating the broad potential of QuGANs across various research fields and industrial sectors.

Keywords: Generative Adversarial Networks. Quantum Generative Adversarial Network. Systematic Literature Review.

Abbreviations: D, Discriminator. GANs, Generative Adversarial Network. G, Generator. PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses. QGANs, Quantum Generative Adversarial Networks. QML, Quantum Machine Learning.

Generative Adversarial Networks (GANs), Variational Autoencoders (VAEs), and Autoregressive Networks are classifications of generative models [1]. GANs were developed in 2014 with the aim of improving the performance of generative models through the use of backpropagation to optimize the network's weights [2].

With their cost function operating as a minimax game, the generative network G and the discriminative network D that compose GANs compete against each other, such that the training of G is probabilistically maximized with the goal of causing D to make an error, while D learns to distinguish whether a data sample comes from G or from the real data distribution [2].

The optimization process of GANs initially proposed can be represented by the equation

$$\min_G \max_D V(D,G) = \mathbb{E}_{x\sim p_{\text{data}}(x)}[\log D(x)] + \mathbb{E}_{z\sim p(z)}\left[\log\left(1 - D\left(G(z)\right)\right)\right] \quad (1)$$

where x is the real sample, z is the random noise vector, G(z) corresponds to the generated data, $\mathbb{E}$ is the expectation, D(x) is the probability that D identifies x as coming from the real data, and

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D(G(z)) indicates the probability that D classifies the data produced by G [1]. G and D are updated as the training process progresses, leading the model to a global optimal solution when D(G(z)) = 0.5 and D can no longer distinguish between the data distributions [1].

GANs resemble a Nash equilibrium, where minimizing the cost function is the objective of each player, with D represented by $J^{(D)}(\theta^{(D)}, \theta^{(G)})$, G represented by $J^{(G)}(\theta^{(D)}, \theta^{(G)})$ and the point $(\theta^{(D)}, \theta^{(G)})$ corresponding to the equilibrium reached, with $J^{(D)}$ at a minimum with respect to $\theta^{(D)}$ and $J^{(G)}$ at a minimum with respect to $\theta^{(G)}$ [3]. However, for the Nash equilibrium to be reached, failures may occur when using gradient-based cost minimization techniques, which can cause the parameters of G to collapse and the result to always converge to the same point [3].

In this context, other GAN-based models have been created, optimizing their performance based on architecture (e.g., convolutional GANs, conditional GANs, and autoencoder-based GANs) and cost function (e.g., unrolled GAN, f- GAN, and WGAN) [1].

The development of Quantum Computing began in 1982 with Richard Feynman, who proposed performing computations on computers using the principles of quantum mechanics [4]. Since then, quantum algorithms have been developed with the aim of solving problems challenging for classical binary logic, such as the Deutsch, Deutsch-Jozsa, Simon, Bernstein-Vazirani, and Shor algorithms [5].

Quantum potential, characterized by quantum speedup, highlights the fact that quantum processors can produce statistical patterns that are computationally hard to find using classical computers, giving rise to Quantum Machine Learning (QML) [6].

By introducing Quantum Generative Adversarial Networks (QuGANs) [7], we show that when G and D are implemented with quantum information processors and the data correspond to measurement samples taken from high-dimensional spaces, QuGANs can demonstrate an exponential advantage compared to classical GANs. Using quantum circuits, it is possible to compute gradients and parametrize the QuGAN model, as illustrated in Figure 1 – General structure of the QuGAN, proposed by Dallaire-Demers and Killoran [8]. The generalization of the comparison between the classical model (GAN) and the quantum model (QuGAN) demonstrates the transformation of the network's processing steps into quantum states, enabling advantages in the execution of the defined architecture.

Just as new research has been developed to optimize classical GANs based on architecture and cost function, the same has occurred with QuGANs, aiming to achieve better results and evaluate applications across different data segments. Therefore, this study's guiding question is: how were QuGANs developed between the years 2018 and 2025?

The general objective of this research is to conduct a systematic literature review of QuGANs during the proposed period, with specific objectives defined as: a) to extract published articles addressing QuGANs within the defined timeframe; b) to compile the types of architectures and applications of QuGANs among the selected works; and c) analyze the results based on this data.

Materials and Methods

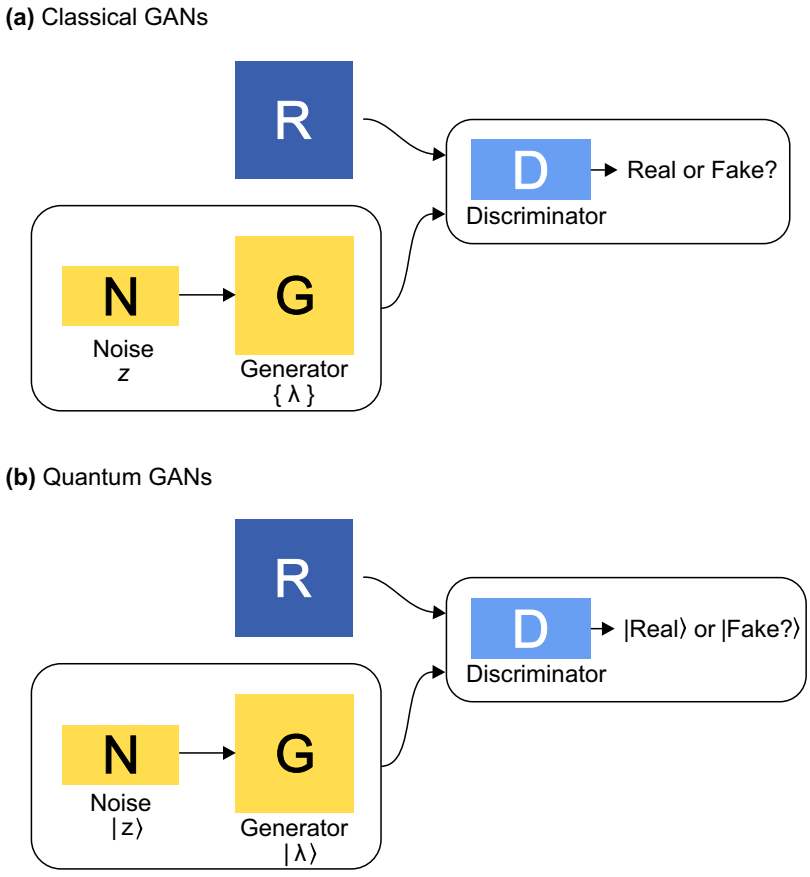
Method

Following the guidelines of the PRISMA 2020 method (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) [9], the systematic literature review was conducted through a search for articles listed in online scientific databases, applying a filter using search terms, covering the years from 2018 to 2025, and limited to articles written in English.

Data Collection

The material used for analysis was extracted from online scientific databases (Scopus: 75; Lens:

Figure 1. General structure of the QuGAN.



254; and Web of Science: 71), filtered using the search terms "quantum GAN" OR "QuGAN" OR "QGAN" OR "QGANs" OR "quantum generative adversarial network" OR "quantum generative adversarial networks." Scientific articles published between 2018 and 2025 were selected, considering the period from when the QuGANs concept was proposed until the time this research was conducted. The online platform Rayyan was used as a tool to apply exclusion criteria, enabling the identification of duplicate works and articles that did not specifically address QuGANs. After obtaining and selecting the remaining works, the software LibreOffice Calc was used to organize a spreadsheet containing the main information from each work (title, authors, abstract, keywords, publication venue, and year). Out of the 400 materials extracted from the indicated scientific databases, 81 were selected for this analysis.

Results and Discussion

The results related to the search for articles in the selected online databases are discussed below, demonstrating the process of selecting publications and systematically analyzing their content based on title, abstract, and keywords. The approaches of the published works are related to research on variations of QuGAN architectures (fully quantum or quantum- classical/hybrid implementations), applications in different areas, optimization processes, and specifications of quantum computing techniques used (including hardware definition for testing and implementation methods).

Results of the Online Database Query

Among the 400 publications, 215 duplicates were removed, leaving 265 to be analyzed. After

identifying duplicate works, those that did not directly address QuGANs were also removed based on an analysis of their titles, abstracts, and keywords. From the evaluated articles, 81 were selected to identify the themes, approaches, and contributions related to the use of QuGANs.

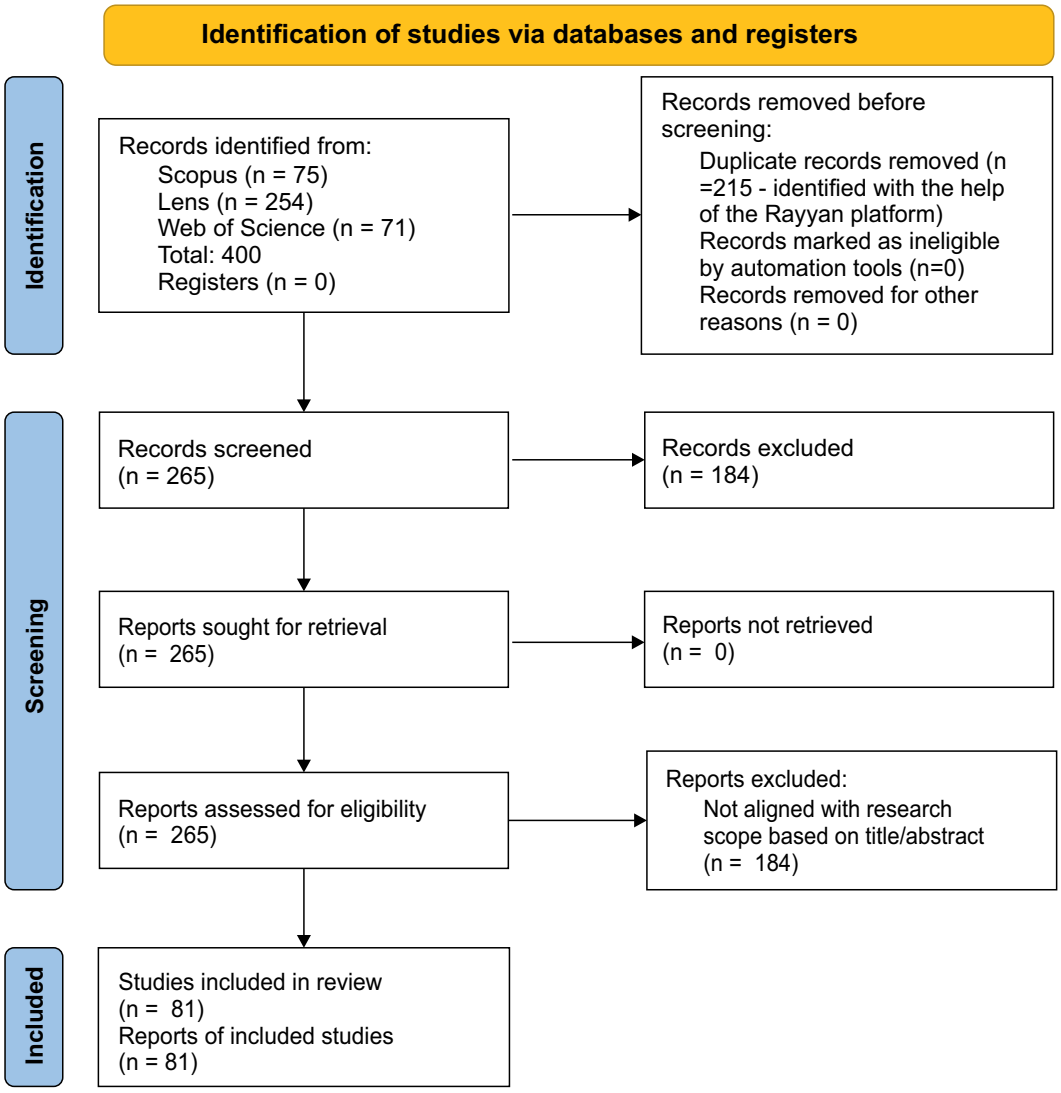
Figure 2 illustrates the process of selecting the articles deemed most suitable for conducting this analysis. The number of research studies related to QuGANs has grown since their initial proposal, indicating a trend toward new investigations over the years. Figure 3 shows the publication count over the years, with 2025 standing out as a notable year for this topic.

Results of the Analyses on the Approaches of the Published Works

In relation to the identification of QuGAN architecture variations (fully quantum implementation or quantum-classical / hybrid), 53 articles reported the use of hybrid approaches [10,11,12,13,14,15,16,17,18, 19, 20, 21, 22, 23, 24,25,26,27,28,29,30,31,32,33,34,36,40,41,42,43,44,45,46,48,50,51,52,53,54,56,58,59,60,61,62,64,66,67,68,69,70,71,73], while only 4 classified their architectures as fully quantum [35,37,38,49].

Figure 4 and Figure 5 compile the identified works, highlighting the type of architecture

Figure 2. Identification of publications according to the PRISMA 2020 method.



(fully quantum and hybrid implementations) and their application areas.

Articles in the area of foundation and theorization of QuGANs stood out in the analysis [11, 15, 16, 18, 20, 27, 28, 30, 34, 35, 37, 38, 39, 47, 49, 52, 54, 55, 63, 65, 66, 67, 68], followed by works in the areas of image generation [13, 19, 26, 31, 32, 40, 60, 64, 70], chemistry and pharmaceuticals [12, 17, 22, 33], quantum error correction [21, 25, 29, 69], high-energy physics [41, 51, 57, 61], experimental implementation [48, 59, 71, 73], medical applications [42, 44, 62], cloud computing [24, 56], anomaly detection [36, 58], telecommunications [45,46], biometrics [10], finance [14], physics and simulations [23], security and cryptography [50], software engineering [43], noise in QuGANs [53], and surveys [72].

Conclusion

This study highlights how QuGANs are being researched and guides future work by revealing a predominance of hybrid architectures, applied in fields such as medicine, chemistry, finance, and security. The trend of increasing publications suggests that future analyses could group applications and architectures to better map the evolution of these networks. In 18 of the 81 articles, classification was not possible, requiring further investigation.

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Figure 3. Number of articles per year.

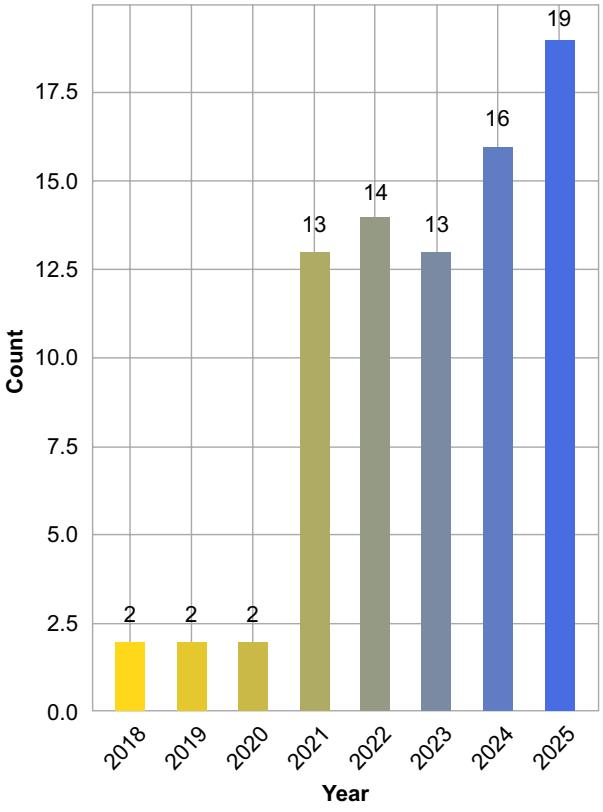


Figure 4. Distribution by architecture.

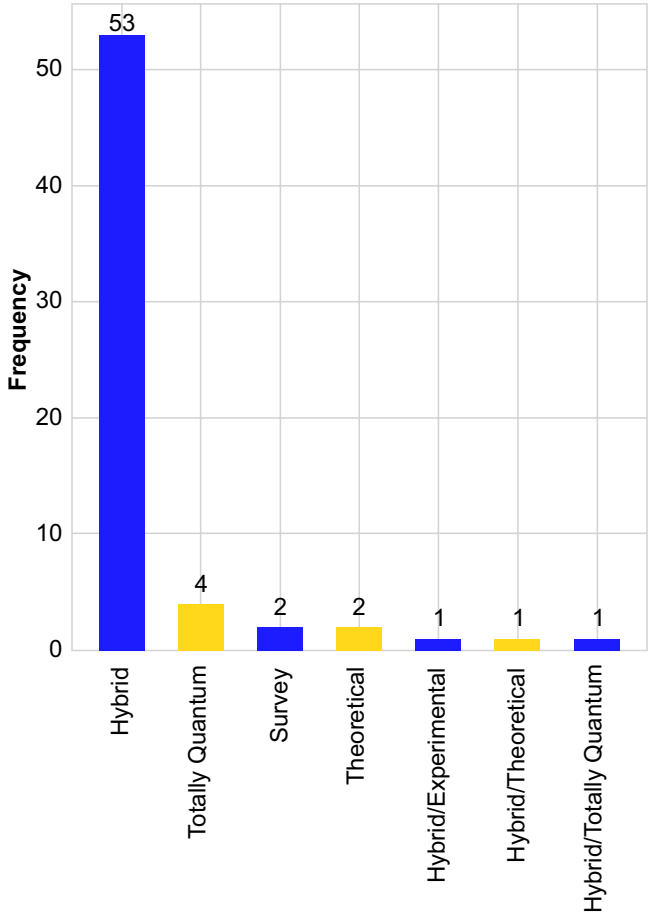
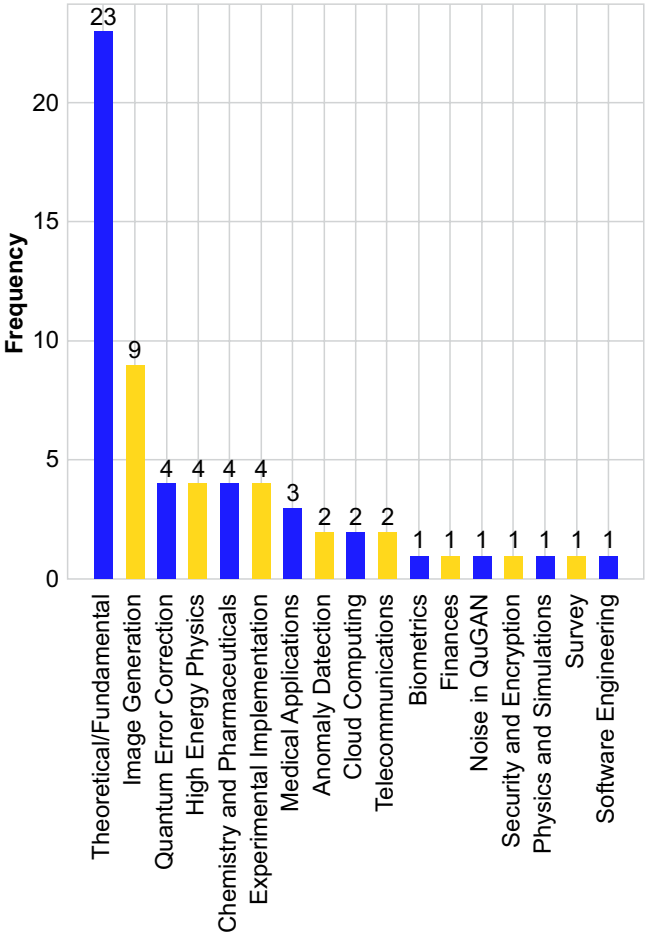


Figure 5. Distribution by application area.



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References

1. Pan Z, Yu W, Yi X, et al. Recent progress on generative adversarial networks (gans): A survey. IEEE Access, 7:36322–36333, 2019.
2. Goodfellow IJ, Pouget-Abadie J, Mirza M, et al. Generative adversarial networks. 2014.
3. Salimans T, Goodfellow I, Zaremba W, et al. Improved techniques for training gans, 2016.
4. Feynman RP. Simulating physics with computers. International Journal of Theoretical Physics, 21, 1982.
5. Portugal R, Marquezino F. Introdução à programação de computadores quânticos. CSBC 2019 – 38º JAI. Belém – Pará, jul 2019.
6. Biamonte J, Wittek P, Pancotti N, et al. Quantum machine learning. Nature 549, 195–202, 2017. https://doi.org/10.1038/nature23474
7. Lloyd S, Weedbrook C. Quantum generative adversarial learning. Phys. Rev. Lett., American Physical Society, v. 121, p. 040502, Jul 2018.
8. Dallaire-Demers PL, Killoran N. Quantum generative adversarial networks. Phys. Rev. A, American Physical Society, v. 98, p. 012324, Jul 2018.
9. Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. BMJ, 2021, 372, n71.
10. Birir KS, Odoyo W, Akinyi L. The Quantum-Assisted Fingerprint Biometrics: a Novel Approach To Fast And Accurate Feature Extraction And Synthetic Generation. In: International Conference on Informatics and Computational Sciences (IC- ITECHS). Bandung, Indonesia: Sekolah Tinggi Informatika dan Komputer Indonesia; 2022.
11. Leadbeater C, Sharrock L, Coyle B, et al. F- Divergences and Cost Function Locality in Generative Modelling with Quantum Circuits. Entropy. 2021;23(10):1281.
12. Sikdar D, Cui M, Chau A, et al. Hybrid Quantum-Classical Generative Adversarial Network for synthesizing chemically feasible molecules. J Emerg Investig. 2023;6:1-8.
13. Pajuhanfard M, Kiani R, Sheng VS. Survey of Quantum Generative Adversarial Networks (QGAN) to Generate Images. International Journal of Quantum Information. 2024;12(23):3852.
14. Pires OM, Nooblath MQ, Silva YAC, et al. Synthetic data generation with hybrid quantum-classical models for the financial sector. Eur Phys J B. 2024;97:178.
15. Ma H, Ye L, Guo X, et al. Quantum Generative Adversarial Networks in a Silicon Photonic Chip with Maximum Expressibility. Adv Quantum Technol. 2024;2400171.
16. Gong C, Wen ZY, Deng YW, et al. Unrolled generative adversarial network for continuous distributions under hybrid quantum-classical model. Laser Phys Lett. 2024;21(12):125207.
17. Kao PY, Yang YC, Chiang WY, et al. Exploring the Advantages of Quantum Generative Adversarial Networks in Generative Chemistry. J Chem Inf Model. 2023;63(11):3307–18.
18. Zoufal C, Lucchi A, Woerner S. Quantum generative adversarial networks for learning and loading random distributions. npj Quantum Inf. 2019;5(1):103.
19. Hu L, Wu S-H, Gao H. Hybrid quantum–classical generative adversarial networks for image generation via learning discrete distribution. Quantum Sci Technol. 2023;8(2):025015.

20. Zoufal C, Lucchi A, Woerner S. Quantum generative adversarial network for generating discrete distribution. npj Quantum Inf. 2019;5(1):103.
21. Braccia P, Banchi L, Caruso F. Quantum Noise Sensing by Generating Fake Noise. Phys Rev Appl. 2022;17(2):024002. DOI:10.1103 PhysRevApplied.17.024002
22. Anoshin M, Sagingalieva A, Mansell C, et al. Hybrid Quantum Cycle Generative Adversarial Network for Small Molecule Generation. In: International Conference on Quantum Technologies and Applications. Cham: Springer; 2022. p. 147-58.
23. Huang YM, Li XY, Zhu YX, et al. Learning Unitary Transformation by Quantum Machine Learning Model. Comput Mater Contin. 2021;68(1):789-803.
24. Liu W, Zhang J, Wu Q. A hybrid quantum-classical conditional generative adversarial network algorithm for human-centered paradigm in cloud. Multimed Tools Appl. 2022;81:22179–96.
25. Tian Y, Tian C, Fan Z, et al. Quantum generative adversarial network with automated noise suppression mechanism based on WGAN-GP. EPJ Quantum Technol. 2025;12(1):80. DOI:10.1140/epjqt/s40507- 025-00372-z.
26. Golchha R, Verma GK. Leveraging Quantum computing for synthetic image generation and recognition with Generative Adversarial Networks and Convolutional Neural Networks. Int J Inf Technol (Singapore). 2024;16(5):3149-62.
27. Liu W, Zhao J, Wu Q. A hybrid quantum-classical generative adversarial networks algorithm based on inherited layerwise learning with circle-connectivity circuit. Quantum Inf Process. 2022;21(11):340.
28. Letcher A, Woerner S, Zoufal C. Tight and Efficient Gradient Bounds for Parameterized Quantum Circuits. Quantum. 2024;8:1484.
29. Tian Y, Zhang Y, Zhang H. Transformer-based quantum error decoding enhanced by QGANs: towards scalable surface code correction algorithms. EPJ Quantum Technol. 2025;12(1):1.
30. Gong LH, Chen YQ, Zhou S, et al. Dual Discriminators Quantum Generation Adversarial Network Based on Quantum Convolutional Neural Network. In: 2023 International Conference on Computer, Information and Telecommunication Systems (CITS). Genoa, Italy: IEEE; 2023. p.1-6.
31. Chen ST, Lee CY, Hsieh MA, et al. HyperKING: Quantum-Classical Generative Adversarial Networks for Hyperspectral Image Restoration. IEEE Trans Geosci Remote Sens. 2025;63:1-15.
32. Tsang SL, West MT, Erfani SM, et al. Hybrid Quantum-Classical Generative Adversarial Network for High-Resolution Image Generation. IEEE Trans Quantum Eng. 2023;4:e124.
33. Li J, Topaloglu RO, Ghosh S. Quantum Generative Models for Small Molecule Drug Discovery. IEEE Trans Quantum Eng. 2021;2:3103308.
34. Anand A, Romero J, Degroote M, et al. Noise Robustness and Experimental Demonstration of a Quantum Generative Adversarial Network for Continuous Distributions. Adv Quantum Technol. 2021;4(5):2100069.
35. Ding Y, Li Z, Zhou N. Quantum generative adversarial network based on the quantum Born machine. Adv Eng Inf. 2025;68:103622.
36. Herr D, O'Malley P, Harrigan MP, et al. Anomaly detection with variational quantum generative adversarial networks. Quantum Sci Technol. 2021;6(4):045014.
37. Niu MY, Zlokapa A, Broughton M, et al. Entangling Quantum Generative Adversarial Networks. Phys Rev Lett. 2022;128(22):220505.
38. Rasmussen SE, Zinner NT. Multiqubit state learning with entangling quantum generative adversarial networks. Phys Rev A. 2022;106(6):062413.
39. Ngo TA, Nguyen T, Thang TC. A Survey of Recent Advances in Quantum Generative Adversarial Networks. ACM Comput Surv. 2023;55(6):1-37.
40. Sedrakyan T, Salavrakos A. Photonic quantum generative adversarial networks for classical data. Optica Quantum. 2024;2(6):458-67.
41. Chang SY, Li L, Valdez L, et al. Dual-Parameterized Quantum Circuit GAN Model in High Energy Physics. IEEE Int Conf Quantum Comput Eng (QCE). 2023;660-70.
42. Qu Z, Shi W, Tiwari P. Quantum conditional generative adversarial network based on patch method for abnormal electrocardiogram generation. Comput Biol Med. 2023;166:107549.
43. Yallamati S, Srikanth V, Nalluri S. Entangling Quantum Adversarial Network with Football Optimization for Software Defect Prediction. Int J Intell Syst Appl Eng. 2023;11(6s):581-90.
44. Bapu BRT, Sivamuni K, Samiappan D, et al. Advanced Detection of Diabetic Foot Ulcers Using Hamiltonian Quantum GANs and Cell Attention Networks, with Genghis Khan Shark Optimization. Biomed Mater Devices. 2025; [DOI:10.1007/ s44174- 025-00332-2].
45. Barik B, Sairam MVS, Naresh N, et al. Channel Estimation for Massive MIMO-OFDM Systems Using Heterogeneous Edge-Enhanced Graph Hamiltonian Quantum Generative Adversarial Networks with Imperfect Channel State Information. Trans Electr Electron Mater. 2025.
46. Ting L, Jinbiao Z. A Novel Broadband Channel Estimation Technique Based on Dual-Module QGAN. KSII Trans Internet Inform Syst. 2024;18(5):1369-89.

47. Kasture S, Kyriienko O, Elfving VE. Protocols for classically training QGMs. Phys Rev A. 2023;108:042406.
48. Hu L, Wu SH, Cai W, et al. Quantum generative adversarial learning in a superconducting quantum circuit. Sci Adv. 2019;5(10):eaav2761.
49. Niu MY, Broughton M, et al. Quantum generative adversarial networks with provable convergence. APS March Meeting. 2021.
50. Luo J, Zhou R, Li Y, et al. Information Hiding Scheme Based on Quantum Generative Adversarial Network. Journal. 2021;33.
51. Chang SY, Agnew E, et al. Running the Dual-PQC GAN on noisy simulators and real quantum hardware. J Phys Conf Ser. 2022;2438(1):012062.
52. Lloyd S, De Palma G, Kiani BT, et al. Applications and experimental realizations of quantum generative adversarial networks. APS March Meeting. 2021.
53. Borras K, Chang SY, Funcke L, et al. Impact of quantum noise on the training of quantum Generative Adversarial Networks. J Phys Conf Ser. 2022;2438:12093.
54. Pan J. Stabilizing quantum GANs. Nat Mach Intell. 2022;2(8):710-8.
55. Ikeda K. Quantum extensive-form games. Quantum Inf Process. 2023;22:13.
56. Selvam PMS, Begum SS, Pingle Y, et al. Optimized Self-Guided Quantum Generative Adversarial Network Based Scheduling Framework for Efficient Resource Utilization in Cloud Computing to Enhance Performance and Reliability. Trans Emerg Telecommun Technol. 2025;36(4):e70120.
57. Agliardi G, Grossi M, Pellen M, et al. Quantum integration of elementary particle processes. Phys Lett B. 2022;832:137228.
58. Kalfon B, Cherkaoui S, Laprade JF, et al. Successive data injection in conditional quantum GAN applied to time series anomaly detection. IET Quantum Comm. 2024;5(3):269-81.
59. Wang Y, Xue S, Wang Y, et al. Quantum generative adversarial learning in photonics. Opt Lett. 2023;48(20):5197-200.
60. Sedrakyan T, Salavrakos A. Photonic Quantum Generative Adversarial Networks for Classical Data. Optica Quantum. 2024;2(6):458-67.
61. Chang SY, Herbert S, Vallecorsa S, et al. Dual-Parameterized Quantum Circuit GAN Model in High Energy Physics. IEEE Quantum Comput Eng (QCE). 2023;2023(660–670).
62. Qu Z, Shi W, Tiwari P. Quantum conditional generative adversarial network based on patch method for abnormal ECG generation. Comput Biol Med. 2023;166:107549.
63. Riofrio CA, Mitevski O, et al. A characterization of quantum generative models. ACM Trans Quantum Comput. 2024;5(2):15.
64. Zhou NR, Zhang TF, et al. Hybrid quantum-classical GANs for image generation via learning discrete distribution. Signal Process Image Commun. 2023;110:116891.
65. Zhu EY, Johri S, et al. Generative quantum learning of joint probability distribution functions. Phys Rev Res. 2022;4(4):043092.
66. Agliardi G, Prati E. Optimal tuning of quantum GANs for multivariate distribution loading. Quantum Rep. 2022;4(1):75-105.
67. Situ H, He Z, et al. QGAN for generating discrete distribution. Inf Sci. 2020;538:193-208.
68. Liu L, Song T, et al. Quantum generative adversarial networks based on Rényi divergences. Physica A. 2022;607:128169.
69. Zhao RS, Ma HY, et al. Quantum generative adversarial networks based on a readout error mitigation method with fault tolerant mechanism. Chinese Phys B. 2024;33(4):044202.
70. Ren W, Li Z, et al. Quantum generative adversarial networks for learning and loading quantum image in noisy environment. Mod Phys Lett B. 2021;35(21):2143043.
71. Huang K, Wang ZA, et al. Quantum generative adversarial networks with multiple superconducting qubits. npj Quantum Inf. 2021;7(1):74.
72. Li T, Zhang S, Xia JY. Quantum generative adversarial network: A survey. Comput Mater Contin. 2020;64(1):401-438.
73. Huang HL, Du Y, et al. Experimental Quantum Generative Adversarial Networks for Image Generation. Phys Rev Appl. 2021;16(2):024051.

Neurodesign of Motor Intention: Frequency–Amplitude–Power Signatures of Mu (8-13 Hz) and Beta (13-30 Hz) Rhythms for Enhanced Decoding of Human Movement Intention

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Sensorimotor Mu (8–13 Hz) and Beta (13–30 Hz) rhythms constitute robust electrophysiological fingerprints of cortical dynamics accompanying the planning, execution and cessation of voluntary movement. To clarify how these spectral signatures can be harnessed in non-invasive brain–computer interfaces (BCIs) for neuro-adaptive feedback systems, a systematic review of studies published between January 2015 and July 2025 was undertaken (in addiction to others to elucidate clinical and technical concepts). Four databases (PubMed, Scopus, Embase and IEEE Xplore) were searched for adult EEG research addressing motor preparation, execution, imagery or action observation. After the eligibility screening, 35 articles satisfied all inclusion criteria. Most experiments employed, at least, thirty-two scalp electrodes 0.5–40 Hz, band-pass filtering and artefact rejection via independent component analysis. Across protocols, contralateral Mu/Beta power fell (event-related desynchronisation) over sensorimotor cortex during real or imagined movement, followed by a rapid Beta rebound (event-related synchronisation) signalling cortical re-inhibition. Peak Mu (~10 Hz) and Beta (~20 Hz) frequencies varied modestly among participants, indicating that individual calibration can enhance single-trial classification accuracy. Transient Beta bursts lasting under 200 ms consistently marked movement termination, whereas stronger Mu suppression correlated with superior performance for neurofeedback of post-stroke rehabilitation tasks. Several studies also reported task-dependent Beta–Gamma coupling and attentional modulation of Mu amplitude as emerging control variables. By mapping where, when and how strongly these rhythms fluctuate, the review delineates clear feature-selection targets and adaptive-threshold guidelines for next-generation BCIs aimed at motor learning and recovery.

Keywords: Beta Bursts. Brain-Computer Interface. Electroencephalography. Event-Related Desynchronization. Motor Imagery. Neurorehabilitation. Post-Movement Beta Rebound. Sensorimotor Rhythms (Mu/Beta).

Abbreviations: BCI, brain–computer interface. EEG, electroencephalography. ERD, event-related desynchronization. ERS, event-related synchronization. Hz, hertz. PMBR, post-movement Beta rebound. NREM, Non-Rapid Eye Movement sleep. SWS, Slow-Wave Sleep. TBI, Traumatic Brain Injury. BOLD, Blood-Oxygen-Level Dependent.

The present systematic review synthesises EEG studies published in the last two decades that examined Mu and/or Beta ERD/ERS during motor preparation, execution, imagery or action observation in healthy adults [1-3].

Aiming to map the spatiotemporal characteristics (peak frequency, onset latency, burst rate) of Mu/Beta modulation across paradigms, while identifying best practices in signal acquisition, preprocessing and feature extraction that maximise signal-to-noise ratio [4-9].

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Therefore, providing evidence-based recommendations for adaptive thresholding and personalised calibration in next-generation BCIs targeting motor intention recognition for post-stroke recovery [10-12].

Building on recent work showing that individual differences in Beta dynamics predict short-term visuomotor learning [10].

Electroencephalographic Signals

Oscillatory electrical activity in the adult brain is conventionally grouped into partially overlapping frequency bands, each associated with characteristic functional states and neurocognitive processes (Table 1).

Table 1. Neural frequency bands.

Band	Range (Hz)	Predominant functional state (In adults)
Delta	0.5 – 4	Deep NREM (slow-wave) sleep, homeostatic regulation [4,13]
Theta	4 – 8	Drowsiness, episodic memory encoding, spatial navigation; sensitive marker in mild TBI [13,14]
Alpha	8 – 13	Eyes-closed rest, sensory suppression, attentional gating [15-17]
Mu (sensorimotor α)	8 – 13 (central)	Sensorimotor "idling," modulated by action observation and motor imagery [1,3,8]
Beta	13 – 30	Motor set maintenance, cortico-muscular coupling, post-movement rebound/inhibition [6,10,18]
Gamma	30 – 100 (low γ) 60 – 200 (high γ)	Local cortical computation, perceptual binding, movement intention decoding [4,8]

Classical boundaries have been complemented by more recent approaches that decompose spectra into periodic and aperiodic components, affording finer-grained parameterization of oscillatory peaks beyond rigid band limits [4].

The borders are heuristic, inter-individual shifts are common, especially around the individual alpha peak frequency, yet the taxonomy provides a useful scaffold for interpreting spectral analyses in motor-cognitive research [4-5, 13].

Sensorimotor Oscillations

Decoding voluntary action from scalp EEG hinges on two rhythmical fingerprints generated in the peri-Rolandic cortex seen in Figure 1: the Mu (∼8–13 Hz) and Beta (∼13–30 Hz) bands.

Both reflect synchronous membrane potential fluctuations within pyramidal-interneuron networks; yet their task-related modulations diverge in timing and functional meaning.

During real or imagined movement, the power of contralateral Mu and low-Beta falls abruptly—an event-related desynchronization (ERD)—signalling the release of local inhibitory gating and the build-up of cortico-spinal drive [10-12,18].

Upon movement termination, a transient Beta rebound, or event-related synchronization (ERS), restores cortical inhibition and is thought to index sensory re-afference processing and motor set re-establishment [6].

These dynamics are reliable enough that single-trial Mu/Beta ERD magnitudes can predict movement kinematics, BCI cursor trajectories or neurofeedback learning rate [3, 11, 21]. Despite such regularities, the extraction of unequivocal movement "intention" markers is non-trivial because:

(i) oscillatory bursts are brief (< 200 ms) and spatially overlapping.
(ii) inter-individual peak frequencies drift with age and cortical physiology [5].
(iii) spectral estimates mix periodic and aperiodic components that inflate power-law baselines [4].

Consequently, high-density arrays (≥32 channels) with artefact-suppression pipelines, preferably independent component analysis, remain standard to maximise the sensor-level signal-to-noise ratio [7, 9].

Within the context of motor-imagery BCIs, Mu/Beta suppression emerges slightly earlier (≈ 200

Figure 1. Perirolandic-cortex representation [19].

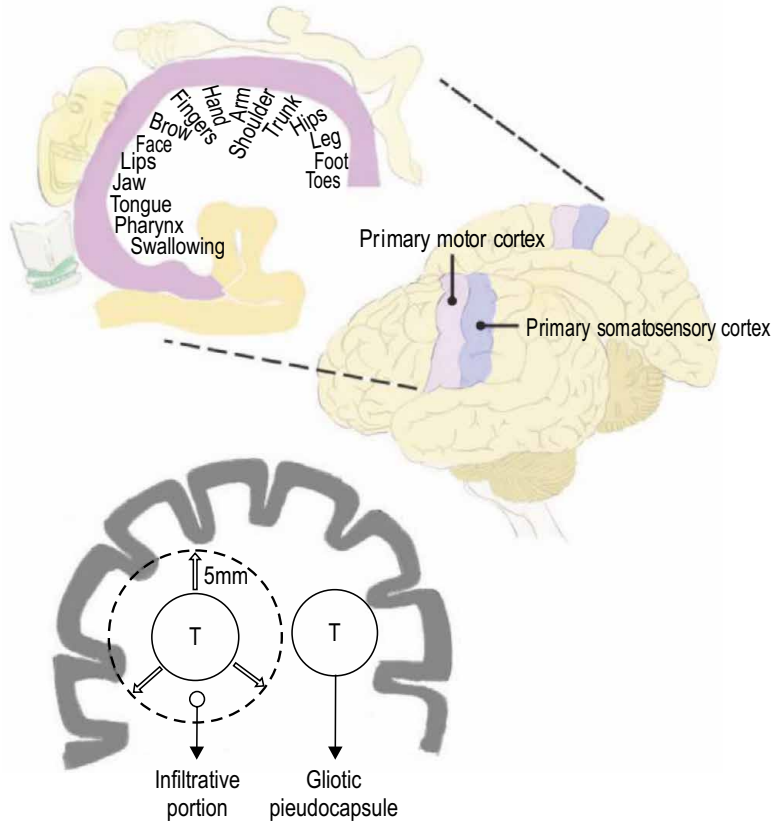
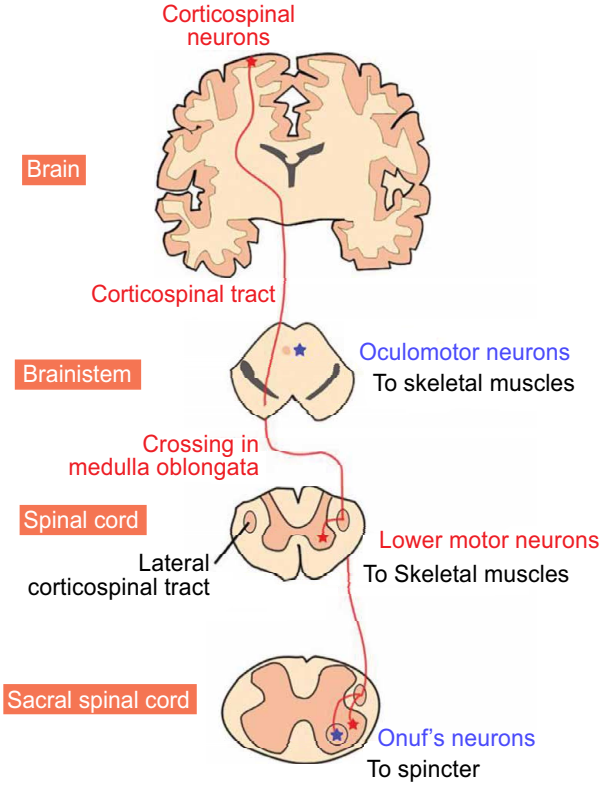


Figure 2. Corticospinal tract [20].



ms pre-cue) and is sustained longer than during overt execution, reflecting the sustained efference copy without peripheral feedback [22-24].

Classification pipelines that incorporate subject-specific peak frequency windows (~ ±2 Hz around the individual alpha frequency) and track the stochastic occurrence of Beta bursts, rather than mean power, achieve superior accuracy especially under adaptive thresholding schemes [2,21].

Collectively, these findings reaffirm Mu/Beta ERD/ERS as the most informative spectral proxies of sensorimotor intent yet also expose the need for personalized calibration and advanced burst-aware feature engineering—issues systematically explored in the present review.

Mu and Beta Oscillations

Sensorimotor oscillations in the Mu (8 – 13 Hz) and Beta (13 – 30 Hz) ranges provide a non-invasive electrophysiological window on the cortical states that precede, accompany and follow voluntary movement [9-10, 12].

During motor preparation and execution, power in both bands decreases, a phenomenon classically termed event-related desynchronisation (ERD). Whereas movement termination is followed by rapid resynchronisation, most prominent in the Beta band, known as the post-movement Beta rebound (PMBR) or event-related synchronisation (ERS) [6,10-12].

These rhythmic signatures have become central features for decoding motor intention in EEG-based brain–computer interfaces (BCIs) and for designing neuro-adaptive feedback aimed at motor rehabilitation [8, 11-12, 21-22].

Transient Beta Bursts

Single-trial analyses consistently reveal brief (< 200 ms) Beta bursts time-locked to movement offset, which coincide with cortico-spinal inhibition and precede the broader post-movement Beta rebound [6].

Their stereotyped latency and high signal-to-noise ratio make them attractive features for asynchronous BCI “stop” commands, complementing the slower PMBR envelope [21-22].

Simultaneous EEG–fMRI further shows that spontaneous Mu power is negatively correlated with BOLD in sensorimotor, dorsal-attention and putative mirror-neuron regions, while showing positive correlations with salience-network nodes such as the anterior insula and anterior cingulate cortex [9].

In addition, two studies reported task-specific Beta–Gamma phase-amplitude coupling that discriminated left- *versus* right-hand motor imagery above chance level, indicating a potential multiband control variable for next-generation BCIs [8].

Materials and Methods

After automated and manual de-duplication, 463 unique titles and abstracts were screened. Title-and-abstract appraisal excluded 405 reports, leaving 58 full papers for eligibility assessment; 23 were discarded for reasons such as paediatric cohorts, invasive recordings or inadequate spectral detail. Thirty-five studies fulfilled every inclusion criterion and composed the evidential core of this review.

The four-database research strategy retrieved 627 records (PubMed = 235; Scopus = 192; Embase = 128; IEEE Xplore = 72), mostly from 2015 to 2025.

All included investigations enrolled healthy adults (18–35 years in 76 % of samples) or non-degenerative clinical populations. Most used 32–64 Ag/AgCl scalp electrodes, 0.5–40 Hz on-line filters and independent-component analysis for artefact rejection. Task paradigms comprised executed movement, kinaesthetic motor-imagery, action observation and combined observation-imagery neurofeedback [7,11, 25-27].

Across experiments, Mu (~10 Hz) and Beta (~20 Hz) event-related desynchronisation (ERD)

emerged contralateral to the engaged limb, beginning ~1 s before movement and persisting throughout the motor epoch. Subsequent post-movement Beta rebound (PMBR) peaked 300–600 ms after termination and was centred over medial sensorimotor cortex [6, 10, 12, 18].

Inter-Individual Variability

Individual peak frequencies varied by ≈ ± 1.5 Hz for Mu and ≈ ± 3 Hz for Beta across participants. Calibrating feature extraction to these idiosyncratic peaks, rather than using fixed canonical bands, boosted two-class motor-imagery classification accuracy by 6 % on average [2-5, 21,22].

BCI Applications

When power and weighted cross-frequency features were combined, Beta-ERS reached mean accuracies of 72.8 %, outperforming Mu-ERD (67.4 %) and Beta-ERD (62.2 %) on the same dataset. Ensemble methods such as Random Forest further boosted accuracy to > 80 % for several participants. These figures exceed the statistical two-class chance level of 57.5 % ($p < 0.05$) and approach clinical usability thresholds [2, 8, 22].

Results and Discussion

Action observation — Meta-analytic evidence indicates that Mu suppression during mere observation is smaller and less somatotopic than during execution, challenging its specificity as a pure mirror-neuron marker [1].

Real and imagined movement — In go/no-go and centre-out reaching tasks, Beta-ERD magnitude scaled with force output and reaction time. Whereas stronger Mu-ERD predicted higher imagery-vividness scores during motor-imagery sessions [3,10,18].

Neurofeedback / rehabilitation — In sub-acute stroke training, Beta-ERD amplitude recorded over ipsilesional M1 correlated strongly ($r = 0.71$) with Fugl-Meyer motor-recovery scores, supporting its adoption as a quantitative biomarker for therapy progress [11-12].

Conclusion

This systematic review synthesised two decades of evidence on the spectral behaviour of sensorimotor Mu (8 – 13 Hz) and Beta (13 – 30 Hz) rhythms during motor preparation, execution, imagery and action observation in healthy adults and non-degenerative clinical populations. All studies confirmed a robust, contralateral ERD in both bands that begins ≈ 1 s before movement onset and scales with effector load and task complexity. After movement, a brief post-movement Beta rebound—often manifested as < 200 ms bursts—signaled corticospinal re-inhibition and predicted slower re-initiation of subsequent actions [6,10,12,18].

Three essential converging insights emerged:

1. **Individualised peak frequency matters**. Peak Mu (~ 10 Hz) and Beta (~ 20 Hz) values shifted by 1 – 3 Hz between participants; tailoring band-pass filters and classification features to these peaks boosted two-class BCI accuracy by up to 6-7 % in cross-validation folds [2, 5, 21-22].
2. **Amplitude carries functional meaning**. Larger Mu-ERD amplitudes correlated with better neurofeedback gains in stroke rehabilitation and with reduced BOLD activity in a distributed motor network, indicating efficient cortico-subcortical recruitment. Conversely, stronger PMBR amplitudes indexed greater transient inhibition of M1 excitability [6, 9, 11-12].
3. **Temporal micro-structure is informative**. High-resolution analyses revealed that Beta bursts, rather than sustained power, best distinguished movement termination and error processing, suggesting that next-generation BCIs should incorporate burst-based detectors instead of sliding-window averages [6-8].

Concerning neuro-design implications for neuro-adaptive BCIs, some features are a must-have:

- Use subject-specific Mu/Beta peaks for filter banks and adapt thresholds dynamically across sessions. Include burst-detection algorithms (< 250 ms) to capture PMBR events for real-time state transitions (e.g., command locking).
- Monitor cross-frequency interactions (Beta–Gamma, Mu–Theta) as auxiliary features when tasks demand heightened attention or proprioception [8].

Limitations include heterogeneous electrode montages (32–256 channels), small median sample sizes (n = 18), and under-reporting of sex-specific effects. Meta-analysis was precluded by variability in ERD/ERS quantification, underscoring the need for unified reporting guidelines aligned with IEC 80601-2-26 [28].

Future research should adopt multimodal designs (EEG-fMRI-NIRS) to localise oscillatory generators, explore closed-loop stimulation that entrains Beta bursts for motor recovery and extend investigations to ecologically valid, freely moving paradigms using mobile EEG and ear-EEG setups [9,11,24]. Addressing these gaps will accelerate the translation of Mu/Beta biomarkers into robust, user-centric BCIs for motor rehabilitation and human–machine interaction.

References

1. Fox NA, et al. Assessing human mirror activity with EEG mu rhythm: a meta-analysis. Psychol Bull. 2016;142(3):291-313. doi:10.1037/bul0000031.
2. Tariq M, Trivailo PM, Simic M. Mu-beta event-related (de)synchronization and EEG classification of left-right foot dorsiflexion kinaesthetic motor imagery for BCI. PLoS One. 2020;15(3):e0230184. doi:10.1371/journal.pone.0230184.
3. Wriessnegger SC, et al. Inter- and intra-individual variability in brain oscillations during sports motor imagery. Front Hum Neurosci. 2020;14:576241. doi:10.3389/fnhum.2020.576241.
4. Donoghue T, et al. Parameterizing neural power spectra into periodic and aperiodic components. Nat Neurosci. 2020;23:1655-1665. doi:10.1038/s41593-020-00744-x.
5. Grandy TH, et al. Peak individual alpha frequency qualifies as a stable neurophysiological trait marker in healthy younger and older adults. Psychophysiology. 2013;50(6):570-582. doi:10.1111/psyp.12043.
6. Rhodes E, et al. Post-movement beta synchrony inhibits cortical excitability. Brain Sci. 2024;14:970. doi:10.3390/brainsci14100970.
7. Hamedi M, Salleh SH, Mohd Noor A. Electroencephalographic motor imagery brain connectivity analysis for BCI: a review. Neural Comput. 2016;28(6):999-1041. doi:10.1162/NECO_a_00838.
8. Gwon D, et al. Alpha and high-gamma phase-amplitude coupling during motor imagery and weighted cross-frequency coupling to extract discriminative patterns. NeuroImage. 2021;240:118403. doi:10.1016/j.neuroimage.2021.118403.
9. Yin S, Liu Y, Ding M. Amplitude of sensorimotor mu rhythm is correlated with BOLD from multiple brain regions: a simultaneous EEG-fMRI study. Front Hum Neurosci. 2016;10:364. doi:10.3389/fnhum.2016.00364.
10. Espenhahn S, et al. Cortical beta oscillations are associated with motor performance following visuomotor learning. NeuroImage. 2019;195:340-353. doi:10.1016/j.neuroimage.2019.03.079.
11. Naros G, Gharabaghi A. Reinforcement learning of self-regulated β-oscillations for motor restoration in chronic stroke. Front Hum Neurosci. 2015;9:391. doi:10.3389/fnhum.2015.00391.
12. Bartur G, et al. Changes in mu and beta amplitude of the EEG during upper-limb movement correlate with motor impairment and structural damage in subacute stroke. Clin Neurophysiol. 2019;130(9):1644-1651. doi:10.1016/j.clinph.2019.06.008.
13. Klimesch W. The frequency architecture of brain and brain-body oscillations: an analysis. Eur J Neurosci. 2018;48(7):2431-2453. doi:10.1111/ejn.14192.
14. Kaltianen H, et al. Theta-band oscillations as an indicator of mild traumatic brain injury. Brain Topogr. 2018;31(6):1037-1046. doi:10.1007/s10548-018-0667-2.
15. Foxe JJ, Snyder AC. The role of alpha-band brain oscillations as a sensory suppression mechanism during selective attention. Front Psychol. 2011;2:154. doi:10.3389/fpsyg.2011.00154.
16. Jensen O, Mazaheri A. Shaping functional architecture by oscillatory alpha activity: gating by inhibition. Front Hum Neurosci. 2010;4:186. doi:10.3389/fnhum.2010.00186.
17. Palva S, Palva JM. New vistas for alpha-frequency band oscillations. Trends Neurosci. 2007;30(4):150-158. doi:10.1016/j.tins.2007.02.001.
18. Hervault M, et al. Cortical sensorimotor activity in the execution and suppression of discrete and rhythmic

movements. Sci Rep. 2021;11:22364. doi:10.1038/s41598-021-01368-2.
19. Zuo F, et al. Surgical management of brain metastases in the perirolandic region. Front Oncol. 2020;10:572644. doi:10.3389/fonc.2020.572644.
20. Ragagnin AMG, et al. Motor neuron susceptibility in ALS/FTD. Front Neurosci. 2019;13:532. doi:10.3389/fnins.2019.00532.
21. Korik A, et al. Decoding imagined 3-D hand trajectories from EEG: evidence to support the use of mu, beta and low-gamma oscillations. Front Neural Syst. 2018;12:130. doi:10.3389/fnins.2018.00130.
22. Kim Y, et al. Motor imagery classification using mu and beta rhythms of EEG with strong uncorrelating transform-based complex common spatial patterns. Comput Intell Neurosci. 2016;2016:1489692. doi:10.1155/2016/1489692.
23. Putzolu M, et al. Neural oscillations during motor imagery of complex gait: an hdEEG study. Sci Rep. 2022;12:4314. doi:10.1038/s41598-022-07511-x.
24. Ueda M, et al. Detection of motor-related mu rhythm desynchronization by ear EEG. PLoS One. 2025;20(4):e0321107. doi:10.1371/journal.pone.0321107.
25. Daeglau M, et al. Event-related desynchronization in motor imagery with EEG neurofeedback in the context of declarative interference and sleep. NeuroImage Rep. 2021;1(4):100058. doi:10.1016/j.ynirp.2021.100058.
26. Friesen CL, et al. Combined action observation and motor imagery neurofeedback for modulation of brain activity. Front Hum Neurosci. 2017;10:692. doi:10.3389/fnhum.2016.00692.
27. Coll MP, et al. Cross-modal classification of mu-rhythm activity during action observation and execution suggests specificity to somatosensory features of actions. J Neurosci. 2017;37(24):5936-5947. doi:10.1523/JNEUROSCI.3393-16.2017.
28. Associação Brasileira de Normas Técnicas. Equipamento eletromédico - Parte 2-26: requisitos particulares para a segurança básica e desempenho essencial de eletroencefalógrafos (ABNT NBR IEC 80601-2-26). Rio de Janeiro: ABNT; 2021.
29. Alamia A, et al. Distinct roles of forward and backward alpha-band waves in spatial visual attention. eLife. 2023;12:e85035. doi:10.7554/eLife.85035.
30. Angulo-Sherman IN, et al. Proficiency in motor imagery is linked to the lateralization of focused ERD patterns and beta PDC. J Neuroeng Rehabil. 2025;22:30. doi:10.1186/s12984-025-01571-6.
31. Aridan N, et al. Suppression of EEG mu rhythm during action observation corresponds with subsequent changes in behavior. Brain Res. 2018;1691:55-63. doi:10.1016/j.brainres.2018.04.013.
32. Bollimunta A, et al. Neuronal mechanisms of cortical alpha oscillations in awake-behaving macaques. J Neurosci. 2008;28(40):9976-9988. doi:10.1523/JNEUROSCI.2699-08.2008.
33. Huang WA, et al. Transcranial alternating current stimulation entrains alpha oscillations by preferential phase synchronization of fast-spiking cortical neurons to stimulation waveform. Nat Commun. 2021;12:3151. doi:10.1038/s41467-021-23021-2.
34. Lapenta OM, et al. Motor system recruitment during action observation: no correlation between mu-rhythm desynchronization and corticospinal excitability. PLoS One. 2018;13(11):e0207476. doi:10.1371/journal.pone.0207476.
35. Liu X, et al. The abnormal functional connectivity between the hypothalamus and the temporal gyrus underlying depression in Alzheimer's disease patients. Front Aging Neurosci. 2018;10:37. doi:10.3389/fnagi.2018.00037.
36. Ramsay IK, et al. Individual alpha peak frequency is slower in schizophrenia and related to deficits in visual perception and cognition. Sci Rep. 2021;11:17852. doi:10.1038/s41598-021-97303-6.
37. Voetterl HTS, et al. Alpha peak frequency-based Brainmarker-I as a method to stratify to pharmacotherapy and brain stimulation treatments in depression. Nat Ment Health. 2023;1:1023-1032. doi:10.1038/s44220-023-00160-7.
38. Witzel AJ, et al. Spontaneous alpha-brain dynamics track the episodic content and quality of recollection. J Neurosci. 2023;43(43):7186-7197. doi:10.1523/JNEUROSCI.0816-23.2023.

Proposed Life Cycle Engineering Framework for Emerging Bioprocesses

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This study explores the application of Life Cycle Engineering (LCE) as a means to assess the sustainability of emergent bioprocesses, with a focus on biofuel production. A distinction has been made between LCE and another life cycle-based concept, Life Cycle Assessment (LCA), highlighting LCE as a more comprehensive approach that encompasses social, environmental, and economic aspects. The study is theoretical in nature, drawing on a literature review on both LCE and the *Agave*-based ethanol production process to propose a framework for applying LCE in low Technology Readiness Level (TRL) bioprocesses, aligning with the 7th and 9th Sustainable Development Goals.

Keywords: Life Cycle Engineering. Bioprocesses. *Agave*. Ethanol. Sustainable Development Goals.

Abbreviations: IEA, International Energy Agency. ISO, International Organization for Standardization. LCA, Life Cycle Assessment. LCE, Life Cycle Engineering. TRL, Technology Readiness Level.

According to the IEA's (International Energy Agency) report, Brazil is considered one of the global leaders in the bioenergy sector, being the second-largest producer of bioethanol, the third-largest producer of biodiesel, and the world's largest producer of second-generation ethanol [1,2]. The estimated production of these biofuels in 2022 was 36.89 billion liters, increasing to 42.91 billion liters in 2023 [3]. As this is the main driver of the bioeconomy in this country, the Brazilian government issued two decrees in 2024 to establish the National Bioeconomy Strategy and the National Circular Economy Strategy. The first one aims to align industrial development, biotechnology, and agricultural production with sustainable economic development, and the second one encourages reuse and recycling of materials, waste reduction, and efficient resource use [4,5].

An emerging concept within the field of sustainability is bioeconomy, which refers to an economic model based on strengthening the use of renewable resources and applying biotechnology within production chains [4,6].

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With the rise of this concept, there has been a growing body of research focused on biomass processing, mainly as an alternative to fossil- based sources to mitigate the impacts of climate change. Nevertheless, there are still barriers to innovation in bioprocesses, such as high costs, food security concerns, land use conflicts, the generation of low value-added co-products anwaste, water consumption, and biodiversity loss. This highlights the fact that it is not sufficient for raw materials to be renewable; it is essential to assess sustainability comprehensively throughout the entire production cycle and find sources that can endure climate changes [6,7].

To ensure that such guidelines are effectively implemented, tools are needed to support changes in industry and to aid in the design of new processes, especially regarding the need for circular chains.

Life Cycle Assessment (LCA) is the most widely used approach for measuring the environmental impacts associated with a product and it is one of several methods based on Life Cycle Thinking, standardized by ISO 14040 and 14044. LCA can evaluate the various phases of a product's life cycle, from raw material cultivation to end-of-life (recycling or disposal) or focus on selected stages. Since LCA primarily addresses environmental aspects, similar approaches have been developed to assess economic costs and social impacts as well [8].

In the 1990s, a new approach began to be discussed that would enable the integration of social, environmental, and economic aspects with a focus on designing cleaner processes. This approach is known as Life Cycle Engineering (LCE), a concept similar to LCA but involving a holistic study that encompasses the development of the product, with a techno-economic focus that does not exclude environmental and social considerations [9]. If effectively applied to bioprocesses, LCE could help ensure that a project can meet the United Nation's Sustainable Development Goals (SDGs) 7 and 9, concerning the use of renewable resources, economic growth, and the promotion of innovation and infrastructure for more sustainable industries [10].

The objective of this study was to demonstrate how the concept of LCE is defined within the field, identifying the most relevant aspects to outline a step-by-step procedure for its application in bioprocesses with low Technology Readiness Levels (TRL), with the aim of assessing their sustainability and feasibility.

Materials and Methods

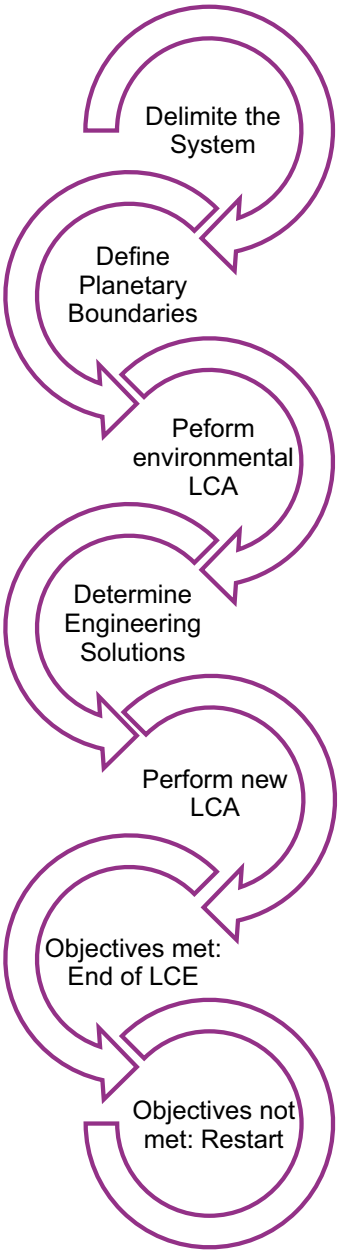
The bibliographic review was primarily conducted using the Scopus database. While additional sources such as ScienceDirect, Google Scholar, Scielo, and CAPES Periodicals were also consulted, Scopus was selected as the main source due to its comprehensive coverage, systematic organization, and the bibliometric data it provides. The terms used were: "Life Cycle Engineering" alone or in combination with "Biomass" or "Biofuel" using the Boolean operator "AND"; a bibliographic search that focused only on relevant reviews of literature on the topic of "Life Cycle Assessment" was also performed for contextualization purposes; and research on an emerging topic — the production of biofuels from *Agave* — was analyzed as a case study to support the development of the steps. Filters were applied only to limit the results to documents in English and categorized as articles, literature reviews, or book chapters. The sequence of study was firstly to conceptualize LCE, then to analyze the existing studies in the field, thus, to examine its relationship with LCA, and then to assess the contributions related to biofuels and *Agave*.

Results and Discussion

Life Cycle Engineering (LCE) is widely defined, in which review studies such as those by Götze and colleagues (2017) [11], Hauschild and colleagues (2020) [12], and Peças and colleagues (2016) [9] conceptualize as an approach that integrates process design with environmental, human, and economic perspectives, also working as a decision-making tool that can employ management concepts such as the Business Model CANVAS and Target Costing. Regarding Life Cycle Assessment (LCA), it is recognized as a well-established approach for analyzing environmental issues when defining processes. In addition to being standardized, it has dedicated software to apply the methodology described in the ISO standards. These features make this approach attractive for addressing the environmental dimension in LCE studies. LCA serves as the foundation for other analysis such as Life Cycle Costing (LCC, for economic aspects) and Social Life Cycle Assessment (S-LCA) [8,9] (Figure 1).

In a recent method, Kara (2023) [13] presented guidelines to be followed for application: delimiting the system to be studied, the planetary boundaries and its spatial allocation; performing an LCA to identify system elements that stand out regarding environmental impacts; determining engineering solutions with existing technologies capable of mitigating these impacts and feasible from a long-term techno- economic perspective; applying these solutions and technologies in the project; conducting a second LCA and, if objectives are not met, restarting the process. These steps are summarized in Figure 1. Among 824 documents in the English language using the keyword "life cycle engineering" in Scopus until 2025, this is the only article that provides well-defined steps for an LCE

Figure 1. Summary of Kara's steps of Operationalization of LCE (2019).



project or study, even though LCA is the core of these steps. The human component involved, and the techno-economic aspect are presented as the IPAT equation considering the local population, Human Development Index, and technology impact relative to the population, which may limit application by not providing clear values and references for the data used in calculations within the article.

Regarding bioprocesses, various considerations arise, since biomass derived from agriculture to be used in an industrial scale requires extensive farming system, causes biodiversity loss, generates atmospheric emissions, may raise food security issues, and the industrial process requires attention to both co-products and waste streams formation [6-8].

LCA is already widely used by practitioners as a sustainability tool in these scenarios, and a holistic study such as LCE could be applied following guidelines adaptable to different bioprocesses, encompassing LCA or other sustainability studies, especially when concerning emergent processes that lack information for such analysis. The only research found on LCE that is related to biofuels was the article by Rahman and colleagues (2023) [14], which conducted a laboratory-scale case study using microalgae as biomass. Regarding Brazil's emergent bioprocesses, although biomass production is focused on sugarcane and soy, plants capable of resisting arid climates have gained prominence and the *Agave* species were chosen as an example in the work by Honorato-Salazar and colleagues [15]. The processes of plants from the *Agave* genus were therefore used as a case study and it was noted that there are few studies in the biofuel sector. Some relevant characteristics of this genus include potential for biofuel generation due to its metabolism capable of sugar accumulation; adaptation to semi-arid regions and use in areas affected by desertification; and its cultivation involves a low technological level. Although no LCE studies exist for this biomass, 18 results were found until 2025 combining the terms "Life Cycle Assessment" and "*Agave*" on Scopus database, in which only 4 of them were related to biofuel and one were concerning *Agave sisalana* (the most produced species in Brazil), which is unrelated to the bioenergy sector [6,15].

The ethanol fuel production process based on tequila production was presented in the LCAs by Parascanu and colleagues (2021) [16], Villardi and colleagues (2024) [17] and Yan colleagues (2020) [18]. These are different studies that show that there is potential for this biomass, but further studies need

Table 1. LCE Framework for bioprocesses.

1. TRL	Evaluate the TRL.
2. Scenarios	Use of Project Management tools such as Proofs of Concept (POCs) and QFD Matrix (Quality Function Deployment) to help creating the desired scenarios.
3. Selection of methodologies	Develop the studies that best fits the project based on the scenarios.
4. Social Impacts	Conduct a social impact analysis, that can be a Social LCA (S-LCA) or *ad hoc* Metrics.
5. Environmental Impacts	It can be prospective LCA, Sustainability Assessments or *ad hoc* Metrics.
6. Selection of the scenario	Select the lowest-impact scenario.
7. Techno-Economic Analysis	Perform a techno-economic analysis, using Life Cycle Costing (LCC), target costing or specialized engineering software.
8. Decision	Re-evaluate the process if techno-economic feasibility is not achieved, returning to Step 2;
9. Conclusion	Final process design for scale-up.

to be conducted so the *Agave* biomasses can have similar level of importance that sugarcane, soy or corn have in the biofuel industry. Based on how these studies were conducted, the presented concept of LCE and Kara and colleagues methodology, a novel framework was developed and were summed in Table 1. It aims to adapt the existing methodology so LCE can be applied in emergent bioprocesses, despite the lack of information. Allying these steps with the exemplified LCAs or new ones can help life cycle practitioners, decision makers and stakeholders to access sustainability and define a perennial design for the bioprocess.

Limitations

While this study provides valuable insights into Life Cycle Engineering, some limitations should be noted. The primary focus of this study was to do a critical review on how Product Development tools and Life Cycle tools can be brought together to help LCE practioners on projects that lack essential information due to novelty. Further studies are going to address a proper case study.

Prospects

Future research may explore the comparison of life cycle impacts across different *Agave* species (e.g., tequilana, sisalana, weber), as well as sensitivity analysis to identify key inventory variables affecting the environmental performance of ethanol production. The inclusion of second-generation (2G) routes and co-product utilization (e.g., cogeneration, bioelectricity, biochar) can further refine system boundaries and improve sustainability and circularity metrics. Additional studies could assess the integration of different renewable energy sources and compare ethanol from *Agave* with other feedstocks such as sugarcane and corn using harmonized functional units and to also provide data for important metrics like RenovaCalc, which is the calculator of Brazilian's Carbon Intensity of Biofuels and can only calculate metrics for soy, sugarcane and corn.

Conclusion

Life Cycle Engineering is a promising approach to analyze sustainability throughout a product's life

cycle. It is a tool that incorporates LCA, techno-economic analysis, and suggests including the social dimension within the assessments, thus offering a more comprehensive study. It can contribute to innovation in industry, including emerging technologies, such as the ones that have been studied in the biotechnology field. It has been illustrated by this present work the biofuel process from *Agave* as a case study, thereby supporting progress toward Sustainable Development Goals 7 and 9. It was observed that adaptations to the operational methodology of LCE could be made to better address certain concept requirements and to better accommodate projects with lower TRL that will be necessary in the bioeconomy that Brazilian Government aims to achieve.

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References

1. International Energy Agency. How competitive is biofuel production in Brazil and the United States? 2019. Available at: https://www.iea.org/articles/how-competitive-is-biofuel-production-in-brazil-and-the-united-states.
2. Statista. Global biofuel production, by country 2023. 2024. Available at: https://www.statista.com/statistics/243887/biofuel- production-in-leading-countries/.
3. Brazil. Brazil's biofuel production grows, reaching historical record. Brasília: Presidência da República, 2024. Available at: https://www.gov.br/secom/en/latest-news/2024/07/brazil2019s- biofuel-production-grows-reaching-historical-record.
4. Brazil. Decreto Nº 12.044, de 5 de junho de 2024: Institui a Estratégia Nacional de Bioeconomia. Brasília: Presidência da República,2024. Availableat: https://www.planalto.gov.br/ccivil_03/_ato2023- 2026/2024/decreto/d12044.htm
5. Brazil. Decreto Nº 12.082, de 27 de junho de 2024: Institui a Estratégia Nacional de Economia Circular. Brasília: Presidência daRepública,2024. Available at: https://www.planalto.gov.br/ccivil_03/_ato2023- 2026/2024/decreto/d12044.htm.
6. Tardy BL, Greca LG, Mihhels K, Lizundia E, Dumee LF, Vega LF, Integrating Arid Areas in the Global Bioeconomy: Opportunities and Challenges toward Sustainable Biomass Generation and Management. ACS Sustainable Chemistry & Engineering. 2023. 11(33), 12177–12193.
7. Lima M, Corporate Power in the Bioeconomy Transition: The Policies and Politics of Conservative Ecological Modernization in Brazil. Sustainability. 2021. 13(12), 6952.
8. Bishop G, Girón-Domínguez C, Gaffey J, Henchion M, Fealy R, Zimmermann J, Kargupta W, Styles D, A life cycle thinking- based environmental risk framework for screening sustainable feedstocks in early-stage bioeconomy projects. Resources, Environment and Sustainability. 2025. 20, 100201.
9. Peças P, Götze U, Henriques E, Ribeiro I, Schmidt A, Symmank C, Life Cycle Engineering – Taxonomy and State-of- the-art. Procedia CIRP. 2016. 48, 73-78.
10. UN. Objetivos do Desenvolvimento Sustentável. Brasília: Nações Unidas - Brasil, 2015. Available at: https://brasil.un.org/pt-br/sdgs. Access: 08/01/ 2025.
11. Götze U, Peças P, Schmidt A, Symmank C, Henriques E, Ribeiro I, Schüller M, Life Cycle Engineering and Management – Fostering the Management-orientation of Life Cycle Engineering Activities. Procedia CIRP. 2017. 61, 134–139.
12. Hauschild MZ, KARA S, RØPKE I, Absolute sustainability: Challenges to life cycle engineering. CIRP Annals - Manufacturing Technology. 2020. 69, 533-553.
13. Kara S, Herrmann, Operationalization of life cycle engineering. Resources, Conservation & Recycling. 2023. 190, 106836.
14. Rahman A, et al, Life cycle engineering (LCE) study for Synechococcus HS-9 biomass production as potential raw material for a third-generation biodiesel production. Sustainable Energy Technologies and Assessments. 2023. 60, 103484.
15. Honorato-Salazar JA, Aburto J, Amezcua-Allieri MA, *Agave* and *Opuntia* Species as Sustainable Feedstocks for Bioenergy and Byproducts. Sustainability. 2021. 13(21), 12263.
16. Parascanu MM, Nestor Sanchez N, Sandoval-Salas F, Carreto CM, Soreanu G, Sanchez-Silva L, Environmental and economic analysis of bioethanol production from sugarcane molasses and *agave* juice. Environmental Science and Pollution Research. 2021. 28, 64374–64393.
17. Villardi HGD, Cruz AI, Cruz VF, Junior ARM, Azzoni S, Pessoa FLP, Simulation of an *Agave* Plant for Ethanol Production. X Simpósio Internacional de Inovação e Tecnologia, Blucher Engineering Proceedings [Internet]. 2024 11;1-10.
18. Yan X, Tan DKY, Inderwildi OR, Smith JAC, King DA, Life cycle energy and greenhouse gas analysis for *agave*-derived bioethanol. Energy & Environmental Science. 2011. 4(9), 3110–3121.

Scientific Communication in Applied Research Groups: A Methodological Proposal Focused on Digital Media

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Scientific communication within applied research groups faces challenges stemming from diverse audiences, varying resources, and distinct institutional contexts, particularly in digital environments. This article proposes a reference model to guide communication strategies tailored to these specificities. The methodology comprised three stages: mapping current practices, identifying barriers faced by researchers, and structuring the reference model. As a result, strategic pillars were established, encompassing objectives, target audiences, communication channels, resources, and evaluation methods, along with adaptation parameters based on group size, research focus, and project characteristics. Rather than offering a one-size- fits-all solution, the model serves as a flexible and reflective tool to support research groups in developing more effective, critical, and socially engaged communication strategies. Future empirical applications may help validate and further refine its usefulness across different contexts.

Keywords: Scientific Communication. Communication Strategies. Reference Models.

Communication can be understood as a process involving the transfer of ideas, thoughts, or feelings between a sender and a receiver, through verbal or nonverbal means. It allows for the expression, planning, and development of strategies, including within the scientific domain [1]. An illustration of its relevance emerged during the COVID-19 pandemic, when intense interactions within the scientific community enabled coordinated responses to the virus. This context appears to have underscored the potential of communication in addressing contemporary challenges by fostering the circulation and democratization of knowledge [2–5].

The democratization of knowledge refers to expanding access to scientific information and involving citizens in the construction and use of such knowledge, within the paradigm of open science [6]. Nevertheless, the same pandemic context also revealed significant challenges, such as the spread of misinformation, which contributed to vaccine hesitancy and undermined immunization efforts [3, 7]. These episodes suggest that traditional scientific communication strategies may prove insufficient in digital environments marked by misinformation, echo chambers, and difficulties in distinguishing verified information from fake news [8].

In this context, science communication no longer seems to function merely as a final stage of the research process; instead, it tends to emerge as a cross-cutting dimension that requires careful planning, mediation, and active engagement with target audiences [9]. However, various structural and cultural barriers continue to hinder this process, including the excessive of technical language, the institutional undervaluing of science outreach, and the lack of specialized training among researchers [10,11]. In Brazil, a country with deep social inequalities, these challenges may become even more complex, further limiting the social reach of science and its capacity to influence local realities [12,13]. While companies and research institutes often maintain formal communication structures, applied research groups typically operate with limited resources and fragmented strategies. As a result, their outputs tend to remain confined to academic environments [14–16].

Information and Communication Technologies (ICTs) appear to offer new opportunities for

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fostering dialogue with diverse audiences. However, their effective use may be constrained by several factors, such as the need to adapt language, unequal internet access, and the absence of robust communication strategies [4, 11]. Despite advances in digital communication, significant gaps still persist in translating scientific content into formats that are more accessible, appealing, and engaging [5]. Initiatives like altmetrics seek to assess the social impact of science through alternative indicators. Still, as Funtowicz and Ravetz [17] caution, such metrics may fall short of capturing the complex interactions between scientific knowledge, social contexts, and citizen participation.

This article seeks to propose a reference model for developing communication strategies tailored to applied research groups. It introduces a conceptual model developed through the mapping of current practices, the identification of key barriers encountered by researchers, and a critical review of relevant literature. The proposed model aims to offer criteria to support the strategic planning of science communication, with the goal of enhancing its reach and social relevance. It is hoped that this approach may help strengthen the social role of science and contribute to the creation of more inclusive and sustainable cities, in alignment with Target 11.3 of the Sustainable Development Goals (SDGs).

Materials and Methods

The methodological approach adopted for the development of the reference model was structured into three stages: mapping current practices, identifying barriers faced by researchers, and structuring the reference model.

Mapping Current Practices

This stage involved a survey and exploratory analysis of how applied research groups communicate their scientific outputs and activities through digital media. Platforms such as LinkedIn, Instagram, YouTube, Twitter/X, institutional websites, open-access repositories, and scientific blogs were considered.

The objective was to identify patterns, gaps, formats, and recurring strategies, with particular attention to the type of language used and the level of engagement with non-specialist audiences. The analysis aimed to understand how these groups adapt their content across different platforms and for various audiences, as well as the communication resources they employ.

Identifying Barriers Faced by Researchers

This stage was based on a literature review focused on the challenges researchers face when translating scientific knowledge into formats that are accessible and comprehensible to broader, non-specialized audiences.

The review considered the following barriers frequently highlighted in the literature on science communication:

- Insufficient communication training;
- Time constraints;
- Lack of institutional support;
- Limited awareness of the importance of science communication;
- Limited proficiency with digital tools.

This analysis was informed by the critical perspectives of several authors [18,19] who examine traditional models of science communication and explore the evolving challenges involved in mediating between science and society. These authors underscore the need for more dialogical approaches—those that are sensitive to sociocultural contexts and capable of fostering meaningful citizen engagement.

Structuring the Reference Model

This stage aimed to define two sets of core elements for the construction of the reference model, based on the systematization of observed practices and the barriers identified in the literature:

- Strategic axes – representing the structural components of science communication within applied research groups;
- Adaptation parameters – serving as contextual variables that guide how the model may be applied according to the characteristics of each group and project.

The organization of these elements followed a modular and flexible structure, intended to facilitate the model's adaptation and replication across diverse institutional, thematic, and operational contexts.

Results and Discussion

Based on the methodological approach outlined, this section presents the main findings from the development of the reference model for communication strategies in applied research groups. The results reflect the decisions and analyses conducted in the previous stages, showing how the strategic axes and adaptation parameters were integrated into the proposed model. Additionally, the discussion explores current challenges in science communication, such as the structural dynamics of social media that often hinder rational discourse, and the phenomenon of clickbait, which can lead to the trivialization of scientific knowledge.

Results

This section outlines the findings from each of the three stages that informed the development of the reference model. First, it presents insights from the mapping of current communication practices, followed by the identification of key barriers faced by researchers. Finally, it details the model's core elements, strategic axes and adaptation parameters, that reflect the synthesis of earlier results.

Mapping Current Practices

The mapping of communication practices across various digital media revealed that each platform has distinct characteristics and affordances, shaping both the type of content produced and audience engagement strategies. Social networks like Instagram and YouTube favor visual and interactive formats, while institutional websites and repositories are more focused on delivering formal and structured content.

In addition, platform algorithms follow specific logics that directly influence content visibility. For example, LinkedIn tends to prioritize posts with strong initial engagement and topics deemed relevant to professional networks, whereas Instagram and YouTube reward posting frequency, audience retention, and the use of native features such as Reels and Shorts [20–22]. These dynamics affect the organic reach of posts and call for platform-specific strategies that consider both content type and algorithmic expectations.

As such, applying a uniform communication strategy across all platforms is neither effective nor desirable, reinforcing the need for a flexible and context-sensitive reference model. Another important finding concerns group size: larger research groups typically have access to dedicated communication resources, whereas smaller groups often face operational constraints that limit both the scope and quality of their outreach efforts.

Identifying Barriers Faced by Researchers

The literature review highlighted that communication barriers vary according to disciplinary field and target audiences. Applied research in areas such as health, environment, and urban planning often requires more accessible and participatory communication approaches, yet these frequently collide with limitations such as insufficient training, excessive workloads, and lack of institutional support [23].

Project-specific factors also emerged as relevant. Initiatives with strong community engagement or public policy relevance tend to require inclusive and collaborative formats, while more exploratory or technical projects often rely on traditional academic dissemination channels

[23]. These distinctions underscore the importance of tailoring communication strategies to the contextual specificities of each research initiative.

Moreover, barriers aren't limited to researchers or institutions alone. The digital platforms themselves introduce structural challenges. Platforms such as Instagram, YouTube, and Twitter/X operate on algorithmic models that privilege content with viral potential, emotional resonance, or polarizing narratives—factors often at odds with the principles of scientific communication. As noted by other authors [24,25], scientific visibility in such environments depends not only on content quality but also on the ability to conform to fast-paced, entertainment-driven formats. This tension between clarity and scientific rigor can lead to the oversimplification or distortion of knowledge.

Thus, beyond the well-documented institutional and individual-level challenges, it is critical to recognize that digital media dynamics have become an additional layer of inequality in the communication of science. This underscores the urgency of developing communication strategies that are critically informed, adaptive, and capable of navigating these environments thoughtfully.

Structuring the Reference Model

Drawing on the previous stages, the reference model was structured around two core components: strategic axes and adaptation parameters.

Strategic Axes define the main dimensions that should guide the planning and implementation of science communication efforts in applied research groups:

- Communication objectives – Clarifying the goals (e.g., dissemination, engagement, education);
- Target audiences – Identifying the segments with which the group intends to communicate;
- Channels and formats – Selecting appropriate media and languages for each audience;
- Capacities and resources – Assessing the team's capabilities, infrastructure, and time availability;
- Evaluation and impact – Establishing metrics to monitor and improve communication outcomes.

Adaptation Parameters serve as contextual filters that allow the model to be adjusted according to the specific conditions of each group or project:

- Group size – Relating to operational capacity and resource availability;
- Research focus – Linked to the scientific and societal objectives of the research;
- Project characteristics – Encompassing complexity, methodology, and intended audience(s).

The interaction between these axes and parameters enables the design of communication strategies that are both flexible and contextually responsive, ultimately aiming to expand the social impact of science.

Discussion

This study aimed to propose a reference model to support the development of science communication strategies in applied research groups. It argues that such strategies should be guided by well-defined structural components and contextual parameters to ensure alignment with the particular institutional, thematic, and operational contexts of each group. In parallel, the analysis draws attention to the digital environments in which scientific communication now largely occurs. These environments are shaped by platform-specific logics that may interfere with the credibility, clarity, and social relevance of scientific content. Effective science communication today, therefore, requires not only technical competence but also a critical understanding of the political and symbolic dimensions of these platforms.

Rather than offering a one-size-fits-all solution, the proposed model acknowledges the heterogeneity of contexts in which science is produced and communicated. By integrating mapped practices with a critical review of persistent barriers, it

aims to enhance strategic decision-making in science communication, especially in terms of public engagement, digital inclusion, and broader knowledge appropriation. Despite its practical contributions, the model doesn't claim to resolve deeper epistemological tensions within science communication, such as the illusion of neutrality or the limits of the deficit model [18, 26]. Nor does it fully address the structural inequalities that hinder science communication in Brazil, including exclusionary language, low levels of scientific literacy, or institutional resistance to dissemination practices [10]. These limitations do not undermine the model's relevance; instead, they highlight important avenues for future research, including empirical validation and theoretical refinement. In the immediate term, however, the model offers a conceptual and operational foundation for applied research groups seeking to structure their communication efforts in a more intentional, reflective, and socially engaged manner.

By recognizing that science communication is a situated and contested practice, this model contributes to the broader goal of strengthening the public presence of science and its role as a driver of social transformation.

Conclusion

The development of a reference model for scientific communication strategies in applied research groups aimed to provide both a conceptual and practical foundation to support researchers in designing more effective and contextually grounded communication actions. Drawing on a three-stage methodological process, the model introduces a structure composed of strategic axes and adaptation parameters, which together account for the diversity of audiences and communication channels, as well as the operational realities of research groups, their fields of activity, and the specific characteristics of their projects.

Rather than offering a purely technical or prescriptive solution, the model acknowledges that science communication is embedded in symbolic struggles, political choices, and ethical dilemmas, particularly within digital environments shaped by algorithmic mediation, visibility pressures, and the spread of misinformation. In this regard, the proposal engages with critical literature by advocating for a situated, dialogical, and strategic approach to science communication, positioning it as an integral, not auxiliary, component of the scientific process.

By systematizing elements that guide the planning and contextual adaptation of communication strategies, the model offers an initial step toward enhancing the communication practices of applied research groups, improving their effectiveness in reaching appropriate audiences with content that is both relevant and accessible. While its empirical implementation remains a subject for future study, the model's immediate contribution lies in providing a practical and adaptable framework that encourages more deliberate, reflective, and socially aligned communication decisions. Future research can help to validate, refine, and expand this model across different institutional, thematic, and disciplinary contexts, contributing to a more inclusive and impactful communication of science.

References

1. Genç R. The importance of communication in sustainability and sustainable strategies. Procedia Manuf. 2017;8:511-516. doi:10.1016/j.promfg.2017.02.065.
2. Dolabella BE. Towards the democratization of knowledge production in public health: lessons learned from a COVID-19 dashboard developed during the COVID-19 pandemic in Rio de Janeiro, Brazil [master's thesis]. San Diego (CA): San Diego State University; 2023.
3. Tambo E, et al. Early stage risk communication and community engagement (RCCE) strategies and measures against the coronavirus disease 2019 (COVID-19) pandemic crisis. Glob Health J. 2021;5(1):44-50. doi:10.1016/j.glohj.2021.02.009.
4. Valeiro PM, Pinheiro LVR. Da comunicação científica à divulgação. Transinformação. 2008;20:159-169.
5. Araújo RF. Marketing científico digital e métricas alternativas para periódicos: da visibilidade ao engajamento. Perspect Ciênc Inf. 2015;20:67-84. doi:10.1590/1981-5344/2402.

6. Mielkov Y. The paradigm of open science and democratization of the research activity of universities. Paradigm Knowl. 2023;3(57). doi:10.26886/2520-7474.3(57)2023.4.
7. Guljaš S, et al. Lack of information about COVID-19vaccine: from implications to intervention for supporting public health communications in COVID-19 pandemic. Int J Environ Res Public Health. 2021;18(11):6141. doi:10.3390/ijerph18116141.
8. Kisa S, Kisa A. A comprehensive analysis of COVID-19 misinformation, public health impacts, and communication strategies: scoping review. J Med Internet Res. 2024;26:e56931. doi:10.2196/56931.
9. Zhang Y, et al. Understanding communication strategies and viewer engagement with science knowledge videos on Bilibili. In: Proceedings of the 2023 CHI conference on human factors in computing systems; 2023; Hamburg, Germany. New York: Association for Computing Machinery; 2023. p. 1-18.
10. Chagas C, Massarani L. Manual de sobrevivência para divulgar ciência e saúde. Rio de Janeiro: SciELO-Editora Fiocruz; 2020.
11. Marques F. Discussão sobre barreiras linguísticas na comunicação científica. Folha de S.Paulo [Internet]. 2023 [citado 2025 set 8]. Available from: https://www1.folha.uol.com.br/ciencia/2023/12/a-barreira-do-idioma-na-comunicacao-cientifica.shtml
12. Guarido Filho ER. Desigualdade social, responsabilidade e responsividade da pesquisa. Rev Adm Empres. 2018;58(5):511-516. doi:10.1590/S0034-759020180507.
13. Yamin E, Gaviraghi FJ. Questão social, brecha digital e tecnologia: expressões de desigualdade na sociedade da informação. Serv Soc Soc. 2023;146(3):e6628318. doi:10.1590/0101-6628.318.
14. Santos SRR, et al. Estratégias comunicacionais organizacionais: desafios e oportunidades [undergraduate thesis]. Manaus: Universidade Federal do Amazonas, Faculdade de Informação e Comunicação; 2024.
15. Madsen RR. Scientific impact and the quest for visibility. FEBS J. 2019;286(20):3968-3974. doi:10.1111/febs.15043.
16. Basantes-Andrade A, et al. Visibility of scientific production and digital identity of researchers through digital technologies. Educ Sci. 2022;12(12):926. doi:10.3390/educsci12120926.
17. Funtowicz SO, Ravetz JR. Science for the post-normal age. Futures. 1993;25(7):739-755. doi:10.1016/0016-3287(93)90022-L.
18. Chagas C, Massarani L. Manual de sobrevivência para divulgar ciência e saúde. Rio de Janeiro: SciELO-Editora Fiocruz; 2020.
19. Bucchi M, Trench B. Science communication: the basics. London: Taylor & Francis; 2025. doi:10.4324/9781032646749.
20. Baram-Tsabari A, Osborne J. Bridging science education and science communication research. J Res Sci Teach. 2015;52(2):135-144. doi:10.1002/tea.21202.
21. Daniel E. Instagram algorithm for reels: how it works and how to beat it. Social Tradia [Internet]. 2025 [cited 2025 Sep 8]. Available from: https://socialtradia.com/blog/instagram-algorithm-reels/
22. Sabu. LinkedIn's algorithm is designed to prioritize meaningful connections. LinkedIn Pulse [Internet]. 2025 [cited 2025 Sep 8]. Available from: https://www.linkedin.com/pulse/linkedins-algorithm-designed-prioritize-meaningful-connections-sabu-rgbfc
23. Etherington D. YouTube demystifies the Shorts algorithm, views, and answers other creator questions. TechCrunch [Internet]. 2023 [cited 2025 Sep 8]. Available from: https://techcrunch.com/2023/08/25/youtube-demystifies-the-shorts-algorithm-views-and-answers-other-creator-questions/
24. De Oliveira Soares I. Meio ambiente: gestão pública e educomunicação. Comun Educ. 2012;17(2):133-136. doi:10.11606/issn.2316-9125.v17i2p133-136.
25. Zuboff S. Surveillance capitalism and the challenge of collective action. New Labor Forum. 2019;28(1):10-29. doi:10.1177/1095796018819461.
26. Latour B. On using ANT for studying information systems: a (somewhat) Socratic dialogue. In: The social study of information and communication technology: innovation, actors, and contexts. 2004. p. 62-76.

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Font Size/Space-Text	12; Double space	12; Double space	12; Double space	12; Double space	12; Double space	12; Double space	12; Double space	12; Double space
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