Analysis of flow characteristics in circular pipes

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Abstract

Determining the fluid flow regime is critical for optimizing oil production processes. To address this need, we evaluated a method for characterizing flow by calculating the Reynolds number. Experiments were conducted using a closed-loop piping system equipped with a flow meter and a visualization chamber. The flow rate was systematically increased, and all tests were performed in triplicate to ensure accuracy and reliability. The results showed that the experimental setup effectively distinguished laminar, transitional, and turbulent flows in both single-phase and multiphase systems, with transitions visually confirmed by observing streamlines. This study presents a validated and practical approach for accurately determining flow regimes, offering direct benefits for the design and operation of industrial flow systems.

Keywords: flow, flow regime, Reynolds number, experimental study.

Análise das características de escoamento em tubos circulares

Resumo

A determinação do regime de escoamento é essencial para a otimização dos processos de produção de petróleo e outras aplicações industriais. Neste estudo, avaliou-se um método prático de caracterização do escoamento com base no cálculo do número de Reynolds. Os experimentos foram realizados em um sistema de tubulação em circuito fechado, equipado com medidor de vazão e câmara de visualização. A vazão foi aumentada gradualmente e cada ensaio foi conduzido em triplicata, garantindo precisão e reprodutibilidade. Os resultados demonstraram que o aparato experimental distinguiu de forma eficaz os regimes laminar, transicional e turbulento, tanto em sistemas monofásicos quanto multifásicos. As transições foram confirmadas visualmente por meio da observação das linhas de corrente, reforçando a confiabilidade do método. Em síntese, este estudo apresenta uma abordagem validada e acessível para a determinação precisa dos regimes de escoamento, com implicações diretas para o projeto, otimização e operação de sistemas de fluxo industriais.

Palavras-chave: escoamento, regime de escoamento, número de Reynolds, análise experimental.

1. Introduction

In 1883, Osborne Reynolds published his seminal investigation into the transition from laminar to turbulent flow in circular pipes, introducing the dimensionless Reynolds number, defined as the ratio of inertial to viscous forces, as the fundamental criterion for predicting flow regimes (Reynolds, 1883). This parameter remains a cornerstone of fluid mechanics, critical for the hydrodynamic scaling and analysis of both internal and external flows across a wide range of engineering applications (White, 2016; Fox et al., 2020).

Flow regimes are distinctly characterized by their Reynolds number. Laminar flow ($Re \lesssim 2300$) exhibits smooth, ordered motion with streamlines remaining parallel and stable. As Re increases, the flow enters a transitional regime ($2300 \lesssim Re \lesssim 4000$), where turbulence begins to sporadically emerge and disrupt the laminar structure. Fully turbulent flow ($Re \gtrsim 4000$) is dominated by stochastic velocity fluctuations, three-dimensional vortices, and intense mixing (Schlichting; Gersten, 2017; Pope, 2000). The precise critical values depend on inlet conditions, pipe roughness, and experimental setup, yet the Reynolds number universally governs the underlying instability mechanism (Drazin; Reid, 2004).

Despite a robust theoretical foundation for single-phase flows, the experimental characterization of multiphase flow regimes, particularly under controlled laboratory conditions, remains less developed. This gap is especially relevant to industrial sectors such as petroleum engineering, where production and transport systems almost exclusively involve multiphase mixtures (Brill; Mukherjee, 1999; Leite et al, 2005a; Leite et al, 2005b). The present study aims to address this by providing an experimentally validated methodology for the unambiguous identification of flow regimes in multiphase systems. The results enhance the predictive capability of transport models and contribute to the improved design and operational safety of industrial flow systems.

In turbulent flows, viscosity and pressure gradients dominate internal flow behavior, whereas in open channels, viscosity and gravity govern the overall dynamics. For external flows, viscous effects are most significant near surfaces—within boundary layers and wake regions downstream of immersed bodies. Pipes, as geometric conduits for forced flow, can take various cross-sectional shapes (circular, rectangular, or elliptical), though circular pipes are the standard for fluid transport.

In pipe flows, confinement by the walls amplifies viscous effects. Experiments with long pipes reveal an entrance region where converging fluid enters the pipe. Along this section, viscous boundary layers grow, slowing flow near the walls while enabling fuller velocity profiles in the central region.

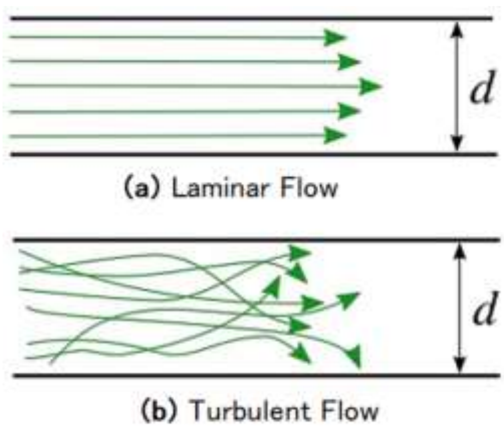

Figure 1. Flow regimes: **a**) Laminar and **b**) Turbulent. Source: Falkovich, 2011.

Multiphase flows, involving two or more immiscible fluids separated by mobile interfaces, are particularly important in the petroleum industry for exploration, processing, and transportation. Such flows exhibit unstable and complex patterns due to interfacial dynamics. Pipelines remain the most efficient method for transporting oil between production sites, offshore platforms, refineries, storage facilities, and end users. Compared to other freight alternatives, pipelines reduce overall costs, minimize truck traffic, and improve road safety.

Because of their critical role, petroleum pipelines require a thorough understanding of flow regimes to prevent leaks, spills, and associated environmental and socioeconomic risks. Calculations for two-phase and multiphase flows are particularly challenging, as phase slippage, flow pattern transitions, interphase mass transfer, and differences in velocity or phase geometry directly affect pressure losses, a key consideration in pipeline design and operation (Silva, 2021).

Several applied studies have expanded knowledge of flow dynamics. López et al. (2020) highlighted the relevance of the Reynolds number in optimizing aircraft aerodynamics and piping systems. Zhou et al. (2022) advanced computational modeling through detailed simulations of flow regimes, while Fauci and Gueron (2020) linked cardiovascular flow patterns to arterial pressure. Kim et al. (2019) further demonstrated that analyzing streamlines and flow parameters provides an effective approach for calculating Reynolds numbers under varying surface conditions.

Building on these insights, the present study experimentally determines flow regimes in vertical pipes, employing systematic measurements of flow rate, temperature, pressure drop, and direct visual observations of streamlines. This dataset supports accurate Reynolds number calculations and flow classification, providing practical validation for computational models and improving the reliability and efficiency of industrial flow system designs.

2. Experimental Methodology

2.1 Apparatus

This work involved experimental studies of fluid flow by measuring flow rate, pressure drop, and liquid level stability in the tank. The experiment (Figure 2) consisted of introducing a colored liquid filament into the center of a pipe carrying an uncolored liquid at controlled velocity.

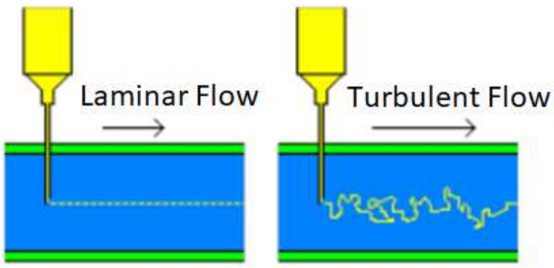

Figure 2. Flow Regime in pipes. Source: Authors, 2025.

As the flow velocity decreased, the colored filament remained straight and continuous along the pipe length until reaching a critical velocity. At this point, the colored line became violently agitated, with its continuity broken by curves and vortices, a clear indicator of turbulent flow. The referenced velocity, identified as the critical velocity based on observed fluid friction, marked the transition from laminar to turbulent flow.

2.2 Procedure

Figure 3 describes the experimental setup used to measure laminar, transitional, and turbulent flow regimes. The procedure involves using water from a stabilized tank and introducing colored dye to visualize the flow behavior and regime type.

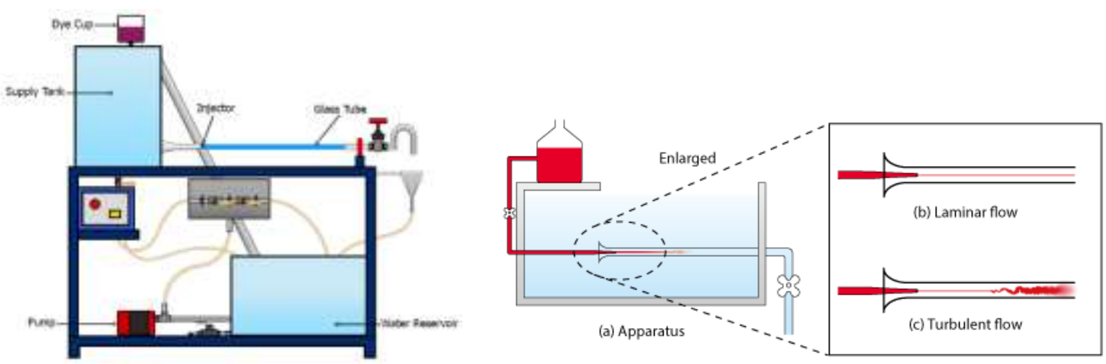

Figure 3. Description of the experimental apparatus used to measure the flow regime in pipes. Source: Authors, 2025.

Therefore, the experimental procedure used in this study involved:

a) Structuring the experimental apparatus, which consisted of a tank filled with water with a fluid inlet coming from a reservoir connected by a pipeline with stabilized flow. A blue dye was injected into the water through a thin tube at the center of the flow stream to allow visualization of the fluid profile as the flow occurred. Thus, the Gunt HM 150 experimental module (Figure 3) was meticulously assembled according to the manufacturer's specifications, and measuring instruments were installed, including pressure sensors and flow meters, all connected and previously calibrated.

b) Laminar flow occurs when the fluid moves in an orderly manner, with parallel layers that do not mix. To observe laminar flow, the flow rate was adjusted to reduce the velocity. In this case, the dye injected into the fluid forms a continuous and smooth line, without visible disturbances, characteristic of low Reynolds numbers, generally below 2,000.

c) As the fluid velocity increases, a condition of turbulent flow is reached, characterized by intense mixing of fluid layers, and the dye disperses in various directions, resulting in an irregular and diffuse flow pattern, associated with higher Reynolds numbers, approximately 4,000.

d) The control of the fluid velocity was carried out by gradually opening the valve or by adjusting the pressure in the inlet reservoir.

e) The visualization of the flow was done by injecting the dye into the water stream to highlight the type of flow, through the uniform streamlines (laminar) and dispersed patterns (turbulent). The use of water as the experimental fluid in fluid mechanics studies is supported by its favorable physical properties, transparency, practical applicability, and safety, characteristics that make water a versatile choice given the demands of various experiments aimed at understanding and modeling fluid dynamics phenomena in different contexts. The choice of methylene blue in fluid mechanics experiments is based on its solubility properties, intense coloration, and flow-tracing capability, characteristics that give the dye a crucial role in the visualization of fluid dynamics phenomena and contribute to the detailed and effective understanding of processes in various experimental applications.

f) The measurement of fluid velocity was carried out with precision using appropriate flow meters, with velocities recorded at different points of the experimental apparatus. The tube diameter dimensions were measured using precision instruments, with the data recorded for later calculation of the Reynolds number.

g) For the development of this work, water was used as the working fluid and methylene blue ($C_{16}H_{18}ClN_3S$) as the dye injected into the fluid to ensure the visualization of the streamlines formed during the experimental trials.

2.3 Calculations

The calculation of the Reynolds number (Re) was performed using experimental data obtained for the fluid velocity, tube diameter, fluid density, and viscosity. These measured values were substituted into the standard equation, $Re = (\rho VD)/\mu$, where ρ is the fluid density (kilograms per cubic meter, kg/m^3), V is the average velocity of the fluid (meters per second, m/s), D is the internal diameter of the pipe (meters, m), and μ is the dynamic viscosity (pascal-seconds, Pa·s or $N\cdot s/m^2$). All values were converted to SI units to ensure consistency during the calculations. By using the experimental measurements directly, the calculated Reynolds numbers reflect the actual flow conditions in the system. The resulting values were then compared to the conventional thresholds, $Re < 2,000$ for laminar flow, Re between 2,000 and 4,000 for transitional flow, and $Re > 4,000$ for turbulent flow, to classify the flow regime accurately.

2.4 Reliability

To ensure the reliability and robustness of the results presented in this work, all experimental trials were conducted in triplicate. Performing the experiments three times under the same conditions minimized random errors and increased the reproducibility of the findings. The data collected from these repeated measurements were subjected to rigorous statistical evaluation, including the calculation of arithmetic means to represent central tendencies and standard deviations to quantify the variability and precision of the results. This approach reduced the influence of potential outliers and enhanced the credibility of the conclusions drawn from the experimental analysis.

3. Results and Discussion

3.1 Visualization of the fluid dynamic behavior

The phenomenological analysis of the data in Figure 4 highlights the characteristics of the streamlines and the relationship between flow velocity and the fluid's physical properties, using as a reference the three flow stages:

a) laminar; b) transitional; and c) turbulent. This analysis is based on the Reynolds number (Re), the main parameter used to determine the flow regime of single-phase, two-phase, and multiphase fluids. Therefore, the visual characteristics of the streamlines are smooth, parallel, and orderly when the flow is laminar (Figure 4a). In this case, the fluid velocity is relatively low, resulting in a calm and organized flow, with a Reynolds number below 2,000.

Laminar flow is primarily governed by the fluid's viscosity, which prevents the occurrence of significant disturbances. Momentum transfer in this regime is dominated by molecular diffusion, resulting in a reduced intensity of transverse mixing between the fluid layers. According to Schlichting & Gersten (2000) and Fox & McDonald (2015), in laminar flow, the fluid layers move smoothly, with little interaction among them, contributing to the stability and predictability of the flow. The viscosity of the fluid plays a crucial role in this behavior, as also observed in Figure 3a, where the dye flows in an orderly manner with no signs of disturbance.

The visual characteristics of the transitional regime (Figure 4b) are identified by small perturbations, with the dye that previously flowed smoothly beginning to distort slightly, with oscillations indicating the loss of laminar flow stability. At this stage, the fluid velocity increases but has not yet reached levels sufficient to generate fully turbulent flow. As reported in the literature, the transition regime between laminar and turbulent flow is highly sensitive to both external and internal disturbances, such as pipe surface roughness and slight variations in pressure and temperature (Pope, 2000; Schlichting; Gersten, 2017). During transition, as described by Schlichting & Gersten (2017), viscous forces still control the flow, but inertial forces begin to play a more significant role as the velocity increases. This unstable balance between forces results in the development of small disturbances that grow exponentially, eventually leading to the onset of turbulence. The phenomenological analysis of Figure 4b perfectly reflects this behavior, with visible oscillations in the dye, evidence of the increasing instability of the flow.

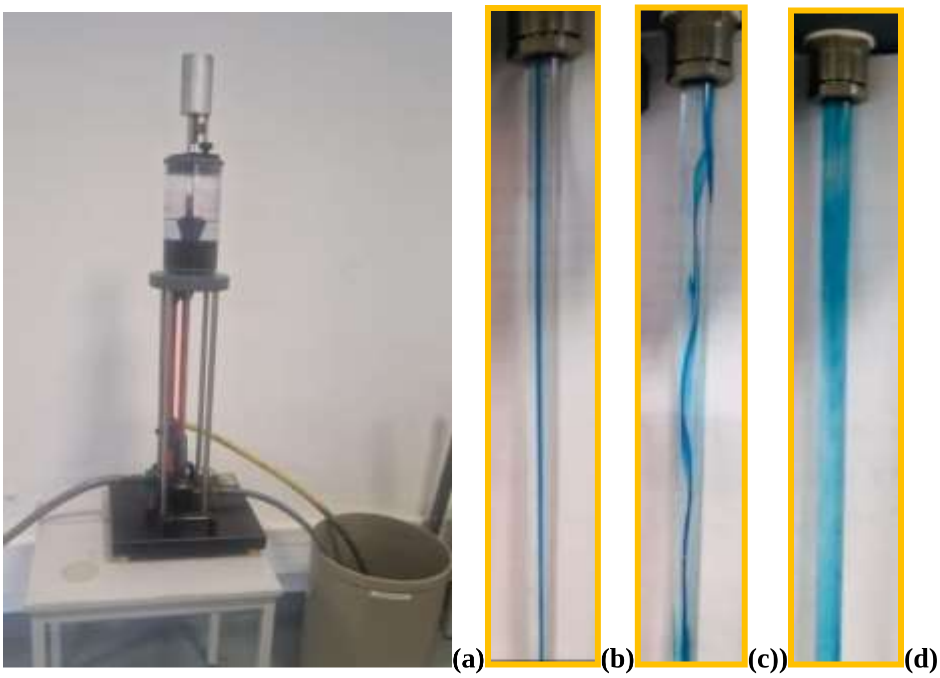

Figure 4. **a**) The Gunt HM 150 experimental module and Laminar (**b**), transitional (**c**), and turbulent (**d**) flow regimes. Source: Authors, 2025.

Finally, the visual characteristics of the dye in the turbulent regime (Figure 4d) exhibit dispersion and chaotic patterns, with streamlines that lose the linearity typical of laminar flow. Strong fluctuations in velocity and direction can be observed within the fluid. In this case, the fluid velocity is high, and the Reynolds number exceeds 4,000, indicating that the flow has entered the turbulent regime, in which inertial forces completely dominate viscous forces, resulting in vortices and rapid flow fluctuations. The literature supported by Çengel & Cimbala (2018) and White (2016) highlights that, in turbulent flow, intense mixing of fluid layers and the presence of vortices are predominant features. This leads to momentum transfer being largely governed by large-scale motions, resulting in intense transverse mixing and consequently higher rates of mass, heat, and momentum transfer within the fluid.

However, turbulence, as discussed by Kim et al. (2011), may be undesirable in applications that require low flow resistance, such as in transport pipelines. This is due to the increased pressure drop associated with turbulence, which implies higher energy consumption to maintain stable flow, making the system less efficient. The observation of velocity and directional fluctuations in the fluid, as shown in Figure 4c, aligns with the literature discussing the challenges of turbulence in fluid transport systems (Zhou et al., 2022).

In this context, the phenomenological analysis of Figure 4 reveals flow behavior that can be predicted and adjusted when the fluid properties and flow conditions are known—highly relevant for the optimization of industrial processes and the understanding of the physical phenomena involved in fluid transport. The literature reinforces the importance of controlling operational conditions, such as fluid velocity, to avoid unwanted turbulence and optimize the efficiency of transport processes. Thus, knowledge of the different flow regimes is essential for the development of more efficient and sustainable systems in various industrial applications.

3.2 Experimental Data Analysis

The Reynolds number is the determining factor that enables the understanding of the transition phenomena from laminar to turbulent flow. In this context, the viscosity of the fluid plays a crucial role in maintaining laminar flow, while the fluid's density and velocity directly influence the transition to the turbulent regime. On the other hand, the transition from laminar to turbulent flow has implications in various areas of engineering, especially in piping systems, aerodynamics, and heat and mass transfer processes, since turbulence increases flow resistance and energy loss. Based on this description, experimental data were collected during the tests, and the results are presented in (Table 1).

The analysis of the experimental data obtained from four distinct fluid flow tests reveals a hydrodynamic trajectory rich in behavioral variations, marked by a progressive transition between the laminar, transitional, and turbulent flow regimes. This variation is observed from the control of flow time and the average liquid volume, allowing the calculation of volumetric flow rate, average flow velocity, and, ultimately, the Reynolds number, an adimensional parameter that guides the classification of the flow regime based on the relationship between inertial and viscous forces.

Table 1. Experimental data obtained.

Experiments	Average Liquid Volume (liters)	Time (s)	Volumetric Flow Rate (L/h)	Flow Velocity (m/s)	Reynolds Number
Exp 1	3,0	26,10	466,13	0,65	6.187,01
Exp 2	3,0	29,05	372,52	0,32	3.045,91
Exp 3	3,0	30,38	352,29	0,25	2.379,62
Exp 4	3,0	40,00	279,22	0,082	780,52

Source: Authors, 2025.

In experiment 4, the lowest Reynolds number (780.52) is observed, corresponding to an average velocity of 0.082 m/s and a flow rate of 279.22 L/h, indicating an unequivocally laminar regime. At this stage, the fluid flows in an orderly manner, with parallel layers sliding over one another without turbulent mixing, which characterizes predictable, smooth, and mathematically more tractable behavior. As the velocity increases in experiment 3, with Reynolds reaching 2,379.62, the system enters an unstable transitional region, where the effects of disturbances are beginning to be felt. This regime is typically characterized by local fluctuations, vortex growth, and the beginning of a complex interaction between the fluid layers, although the flow still retains moments of internal organization.

In experiment 2, the Reynolds number reaches 3,045.91, consolidating the presence of the transitional zone, with a growing tendency towards turbulence. At this stage, the flow behavior can no longer be described solely by simple deterministic laws, as unpredictability and randomness begin to impose themselves. Finally, in experiment 1, the average fluid velocity rises to 0.65 m/s, increasing the Reynolds number to 6,187.01. This value is well above the classical transition threshold, characterizing a fully turbulent regime. The fluid moves with a high intensity of mixing, vortex generation, and the formation of chaotic structures that promote a high rate of heat and mass transfer, but, on the other hand, result in greater pressure loss and require more energy pumping.

This experimental sequence, by systematically controlling the flow velocity, provides a detailed observation not only of the absolute values of the physical parameters but also of the evolution of the fluid system's behavior. This practical and empirical approach illustrates the fundamental principles of fluid mechanics, with the Reynolds number serving as a key diagnostic and predictive variable, allowing the flow to be situated within a continuum between order and chaos (White, 2016). The transition between flow regimes—laminar, transitional, and turbulent- is a critical feature, highlighting the system's sensitivity to variations in operating conditions, such as temperature, pressure, and surface roughness (Smith et al., 2018).

The interpretation of the obtained data goes beyond the simple classification of flow regimes and expands into a deeper understanding of the impact that each regime can have on industrial design and operations. Laminar regimes, with their predictability and stability, are ideal in processes that require strict control, such as microfluidic systems and the flow of sensitive solutions, where a high rate of mixing can impair process efficiency (Patankar, 2019). In contrast, turbulent regimes, with intense mixing and high rates of mass and heat transfer, are desirable in applications such as heat exchangers and chemical reactors, where the goal is to maximize convective transfer (Brennen, 2018).

The transitional regime, with its unstable nature, presents significant challenges both for modeling and for controlling the flow, requiring greater experimental precision and caution in system design. According to Koschatzky et al. (2020), the transition from laminar to turbulent flow can be triggered by small disturbances, such as pressure changes or variations in fluid properties, and is a phenomenon difficult to model due to its intrinsic instability.

Thus, the tests conducted and the data obtained illustrate the fundamental principles of hydrodynamics and also provide a rich basis for reflection on the real behavior of fluid systems and their implications for process design and control. They exemplify the interaction between theory, practice, and applied engineering, an interaction essential for the full mastery of fluid mechanics and its interfaces with the physical world. A deep understanding of these regime transitions, as discussed by Zhang et al. (2022), is crucial for the optimization of industrial processes involving fluid transport, enabling engineers to design more efficient systems with better performance.

4. Conclusions

Based on the results presented here, it can be concluded that:

a) Experimental results confirmed that the Reynolds number is a decisive parameter for flow regime characterization, allowing a clear identification of laminar, transitional, and turbulent ranges.

b) Distinct hydrodynamic behaviors were observed across different Reynolds numbers: low values produced laminar flow, intermediate values marked the transition regime, and high values corresponded to fully developed turbulence.

c) Analysis showed that small variations in operating parameters within the transitional range caused significant shifts in flow behavior, demonstrating the inherent instability of this regime.

d) The close agreement between Reynolds numbers obtained in experiments 1 and 3 confirmed test repeatability and the stability of the experimental apparatus, validating the reliability of the generated data.

e) The deviation observed in experiment 2, compared to the others, highlighted the sensitivity of flow regimes to initial perturbations, geometric inconsistencies, or boundary condition fluctuations, reinforcing the need for strict control in experimental studies.

f) The findings demonstrate direct applicability in engineering systems such as pipeline design and fluid transport modeling, and also provide insights into natural flows in rivers, channels, and atmospheric systems.

g) The study established a basis for future investigations, recommending experiments within narrower Reynolds intervals and the integration of computational fluid dynamics (CFD) to resolve internal flow structures in greater detail.

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6. Authors' Contributions

The authors of this article contributed proportionally, engaged in the development of this work, with greater responsibility given to the students involved in the proposed studies.

7. Conflicts of Interest

The authors declare that there are no competing interests related to the research, authorship, or publication of this manuscript. No financial, personal, or professional relationships, whether direct or indirect, exist that could inappropriately influence the work presented in this study. The authors further confirm that they have adhered to ethical guidelines in conducting and presenting the research, ensuring that the results and conclusions drawn are unbiased and free from any conflict of interest.

8. Ethics Approval

Not applicable (This work did not involve human or animal subjects.).

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