

Linear Buckling of Compressed Carbon or Stainless Steel Columns at Elevated Temperatures

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Abstract: - Under compression and elevated temperatures, carbon or stainless steel columns lose stiffness and strength, leading to earlier global and local buckling and failure. In this work, the main aim is to present an analytical and numerical method that links the column theory to the buckling response at elevated temperatures. Various parametric studies are shown to compare the critical buckling load between the analytical and numerical results using the finite element method. Columns under compression at different temperatures (20, 400, 600 and 800 °C) are assessed. The main goal is to demonstrate that using the finite element method offers an alternative approach for studies involving different materials and shape configurations.

Key-Words: - Column Buckling, Compression, Elevated Temperatures, Finite Element Method, Euler Load, Eurocodes, Carbon Steel, Stainless Steel.

Received: March 12, 2026. Revised: April 23, 2026. Accepted: May 15, 2026. Published: September 29, 2026.

1 Introduction

Carbon steel has high strength, hardness, and durability. But carbon steel columns in compression become highly vulnerable to global and local buckling as temperature rises, especially in thin-walled sections. Other materials, such as austenitic and duplex stainless steels, have been used for structural applications due to their attractive and highly corrosion-resistant properties. At the same time, they have good strength, toughness, and fatigue properties, along with low maintenance requirements. Some limitations of duplex stainless steel columns arise from prolonged service at 250-300 °C due to phase precipitation.

According to the application of the standards, Eurocode 3, part 1-4 [1] gives supplementary provisions for the design of structural engineering works. It extends the application of Eurocode 3, part 1-1 [2], which covers general rules for the structural design of hot rolled and welded carbon steel sections, and Eurocode 3, part 1-3 [3], which covers the structural design of cold formed light gauge carbon steel sections to austenitic and duplex stainless steels.

In the present work, analytical theory for column buckling at elevated temperature will be used due to the extension of the classical Euler approach by including temperature-dependent material properties and often non-uniform temperature fields. The current research combines analytical formulations with finite

element simulations to calibrate design rules at extreme temperature conditions.

Recent work combines experimental tests and finite element models to quantify capacity loss and to refine design rules for such conditions [4]. Thermal buckling is now often treated with temperature-dependent material properties (elastic modulus, yield stress) and nonlinear stability formulations, capturing both pre and post-buckling responses [5]. For uniform or simply supported columns, analytical or semi-analytical approaches extend Euler theory with temperature-dependent stiffness, sometimes via polynomial property temperature relationships [5].

There are some advances in study: high-strength and “fire-resistant” steels, where systematic tests show current Eurocode or other standard curves often inaccurate for hollow structural sections and fire-resistant grades at elevated temperatures, leading to revised flexural and local buckling curves and modified critical-temperature methods [6]; advanced aluminum column design in compression and eccentric loading with finite element databases produced fitted stability coefficients and design formulas outperforming Eurocode approaches [7]; non-uniform temperature and restrained columns as a new analytical and data quality frameworks capture localized fire, restraint, and temperature gradients along tapered columns, including post-buckling paths and ultimate loads; also extreme temperatures at 800-

1000 °C and empirical time-to-buckling correlations relevant to nuclear severe accidents have been established for slender stainless columns; also hybrid and composite systems with temperature-sensitive buckling (carbon fibre reinforced polymer, reinforced steel columns concrete-encased) is being quantified, with personalized modifications to direct strength method and codes.

As future developments in this scientific area, new assignments can be followed: a fully temperature-dependent analytical model that incorporate effects and property polynomials for thermal buckling and post-buckling [8]; a unified elevated temperature direct strength method and effective width method rules for high-strength steels, aluminium, and cold-formed sections, based on finite element test databases [9]; a performance based on fire design tool coupling non-uniform fire scenarios, restraint conditions, creep and composite materials in simplified accurate column models [10].

The main objective of this work is to use the analytical compression column theory applied to the same column subjected to elevated temperatures, and to compare the theory with the numerical model, as proposed, using the finite element method with shell elements. It will also be possible to perform further analytical calculations of columns for different temperature ranges or even using other materials, considering the multiplication of a factor previously obtained in the validation model, which will be useful for direct calculation.

2 Analytical Study of Compressed Carbon or Stainless Steel Columns at Elevated Temperatures

The following analytical methodology is applied to the columns in compression and will be extended to columns at elevated temperatures.

According to the literature, short columns fail with a critical buckling stress that can be larger than the material yield. In this zone, the material no longer performs by elasticity, and the buckling of this region is called inelastic [11], [12].

Columns subjected to an axial load have a limit on their resistance, identical to the material's yield limit f_y , multiplied by the cross-section area A [12], expressed by plastic load N_{pl} , in Equation (1).

$$N_{pl} = A \cdot f_y(1)$$

The long columns will tend to fail under lower loads by elastic buckling, reaching the critical

buckling stress, and it is called elastic buckling [12], or Euler critical load N_{cr} .

The elastic critical load N_{cr} gives the value of the slenderness of a member in compression [12] according to Equation (2).

$$N_{cr} = \frac{\pi^2}{L_e^2} E \cdot I(2)$$

where: E is the modulus of elasticity, and I is the minimum moment of inertia. For columns with fixed-free ends, the effective length L_e is equal to 2 times the column length L [12]. For columns, the same boundary conditions will be applied.

However, while the previous relationship represents the ideal theoretical fixed-free condition, total rotational restraint at the base is rarely achieved in real structural assemblies. Partial rotational restraint resulting from the base's flexibility can affect the actual effective length, making the buckling load predictions highly constraint sensitive. This emphasizes the importance of evaluating how boundary parameters correlate with real-world structural behavior.

The non-dimensional slenderness $\bar{\lambda}$ is obtained according to Equation (3), a function of the cross-section A , the yield stress f_y and the critical load N_{cr} . As for the non-dimensional slenderness corrected for elevated temperatures $\bar{\lambda}_T$, obtained in Equation (4), it depends on the previous variable and on the evolution of the mechanical properties of the material as a function of the temperature T .

$$\bar{\lambda} = \sqrt{\frac{A \cdot f_y}{N_{cr}}}(3)$$

$$\bar{\lambda}_T = \bar{\lambda} \cdot \sqrt{\frac{k_{y,T}}{k_{E,T}}}(4)$$

These equations represent fundamental parameters that allow for the determination of the reduction factor for buckling.

The studied columns in carbon steel material S235 [2] have a modulus of elasticity of 210 GPa and a yield stress of 235 MPa, at ambient temperature. At elevated temperatures, the yield stress and the modulus of elasticity decrease depending on the reduction factor from Eurocode 3, part 1-2 [13], as shown in Table 1. It should be noted that the yield strength for carbon steel is reduced only after exposure to temperatures over 400 °C, unlike what is stated for stainless steel in the Eurocodes, in which both strength and stiffness gradually decrease.

Table 1. Mechanical properties of steel material S235

$T, ^\circ\text{C}$	f_y, MPa	E, GPa	$\sqrt{\frac{k_{y,T}}{k_{E,T}}}$
20	235.00	210.00	1
400	235.00	147.00	1.195
600	110.45	65.10	1.231
800	25.85	18.90	1.106

Source: [2], [13]

The studied columns in stainless steel material [1] have a modulus of elasticity of 200 GPa and a yield stress of 309.6 MPa [14], at ambient temperature. At elevated temperatures, the yield stress and the modulus of elasticity decrease depending on the reduction factor from Eurocode 3, part 1-4 [1], as shown in Tables 2 and 3. The yield stress values for stainless steel were obtained according to the proposal of Annex C of Eurocode 3, part 1-2 [13]. This approach allows using stress at 2% total deformation as the characteristic strength parameter for these materials. The behavior of stainless steel varies from that of other metals at fire temperatures [14]. The yield strength of stainless steel depends on the alloy of the material according to the chosen stainless steel grade [14].

Table 2. Mechanical properties of stainless austenitic steel material EN1.4401/1.4404

$T, ^\circ\text{C}$	f_y, MPa	E, GPa	$\sqrt{\frac{k_{y,T}}{k_{E,T}}}$
20	309.60	200.00	1
400	218.40	168.00	0.916
600	192.00	152.00	0.903
800	124.80	126.00	0.800

Source: [1]

Table 3. represents the dimensions and the geometric characteristics of the studied columns. All geometric parameters allow the calculation of the mass geometry (A and I) needed to be used in previous equations: L is the column length; B is the width of the square cross-section, and t is the column thickness

Table 3. Characteristics of the columns with square cross-section

L, mm	B, t, mm	A, mm^2	I, mm^4
1000	$B=50$ $t=3$	564	208492
2000			
3000			
1000	$B=60$ $t=3$	684	371412
2000			
3000			
1000	$B=70$ $t=3$	804	602732
2000			
3000			

Source: created by the author

3 Numerical Study of Compressed Carbon or Stainless Steel Columns at Elevated Temperatures

A numerical program was used to simulate the critical load in columns. Ansys® program based on the finite element method was chosen.

For this type of simulation, a shell element SHELL181 with 4 nodes and 6 degrees of freedom per node was selected. This element is suitable for analyzing thin or moderately thick shell elements, for linear, high rotation, and/or large nonlinear deformation applications [12]. A mesh size with a length of 10 mm was imposed in all numerical models after a convergence criterion was met.

The numerical procedure with the Ansys® program employs a linear eigenvalue buckling analysis to extract the elastic buckling mode shapes of each column. These eigenmodes are then normalized and scaled to a prescribed imperfection amplitude, providing representative local buckle shapes that are introduced into the column geometry for subsequent nonlinear or parametric analyses for future work in this research. Pre-stress effects reinforce the computation of the stress stiffness matrix. This is completed by first completing a structural analysis on an ideally loaded structure and then evaluating the stress field to continue a modal analysis that results in the buckling mode. The eigenvalue solver applies a unit load on the column to establish the needed buckling load [12]. For columns, the first few eigenmodes often represent local buckling patterns (one, two, or more half-waves across the panel). The first mode represents the obtained critical mode $N_{cr,A}$. In practice, extract the relevant local buckling mode shape, and multiply this mode by a chosen amplitude to obtain a scaled imperfection field [15].

According to the numerical procedure, Figure 1 shows the results of a column ($L=1000$, $B=50$, $t=3$) mm, with a fixed end at the bottom (all degrees of freedom constrained) and a free end at the top, where the load will be imposed. In this figure, it is possible to identify the mesh type, the first buckling mode, which corresponds to the critical Euler load 116.48 kN, the deformed shape, the lateral displacement, and the plastic stresses obtained from a plastic load of 142.49 kN, which represents a relative error of 6.98% in relation to the analytical plastic value. The other numerical results in all columns represent the same behavior, but with different critical load values presented in the next chapter.

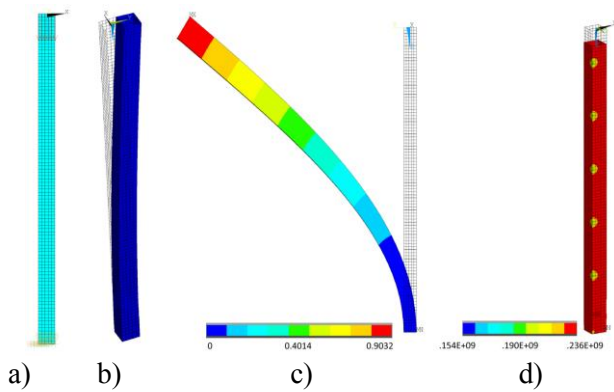


Fig. 1: Numerical column: a) mesh, b) buckling mode, c) deformed and lateral displacement in m, d) plastic stresses in Pa

Source: created by the author

4 Results and Discussion

Table 4 and Table 5 present all analytical values from equations (1) and (2) and the numerical results, both at ambient temperature, for each used material. A relative error E_{cr} is also calculated in relation to the analytical method.

Table 4. Analytical N_{pl} , N_{cr} , and numerical N_{cr_A} critical loads at ambient temperature in carbon steel S235

B, t, mm	L, mm	$\bar{\lambda}$	N_{pl}, kN	N_{cr}, kN	N_{cr_A}, kN	$E_{cr}, error \%$
$B=50$ $t=3$	1000	1.11	132.54	108.0	116.5	7.82
	2000	2.22		27.0	29.3	8.31
	3000	3.32		12.0	13.0	8.38
$B=60$ $t=3$	1000	0.91	160.74	192.5	204.1	6.03
	2000	1.83		48.1	51.5	6.93
	3000	2.74		21.4	22.9	7.05
$B=70$ $t=3$	1000	0.78	188.94	312.3	325.3	4.15
	2000	1.56		78.1	82.7	5.86
	3000	2.33		34.7	36.8	6.05

Source: created by the author

Table 5. Analytical N_{pl} , N_{cr} , and numerical N_{cr_A} critical loads at ambient temperature in stainless austenitic steel material EN1.4401/1.4404

B, t, mm	L, mm	$\bar{\lambda}$	N_{pl}, kN	N_{cr}, kN	N_{cr_A}, kN	$E_{cr}, error \%$
$B=50$ $t=3$	1000	1.30	174.61	102.89	110.93	7.82
	2000	2.61		25.72	27.86	8.31
	3000	3.91		11.43	12.39	8.37
$B=60$ $t=3$	1000	1.07	211.77	183.28	194.34	6.03
	2000	2.15		45.82	49.00	6.93

	3000	3.22		20.36	21.80	7.05
$B=70$ $t=3$	1000	0.91	248.92	297.44	309.79	4.15
	2000	1.83		74.36	78.71	5.87
	3000	2.74		33.05	35.05	6.06

Source: created by the author

The Euler critical load is higher in columns with lower slenderness in each square column in the study. The plastic load increases according to the increased cross-sectional area of the column. The numerical results agree with the analytical values, with an average relative error of Y equal to 6.73%, calculated in each Tables 4 or 5.

With the average relative error Y , and for square columns with fixed-free ends, it will be possible to calculate the numerical value of the Euler critical load at elevated temperatures, where only the modulus of elasticity is changed according to Tables 1 or 2. The proposed equation will be:

$$N_{cr_A} = Y \cdot N_{cr}(6)$$

The previous results from Tables 4 and 5 are shown in Figure 2, with the obtained curves of the Euler critical load in relation to the plastic load vs the non-dimensional slenderness, at ambient temperature.

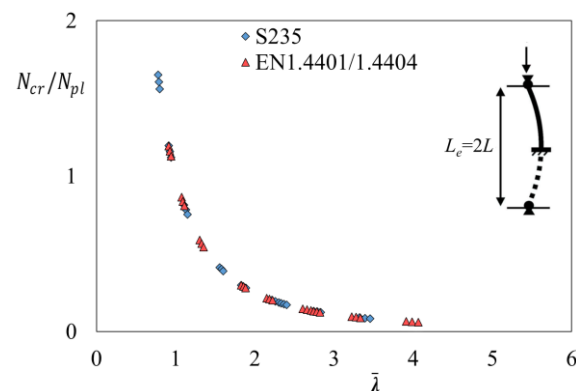


Fig. 2: Critical loads vs. non-dimensional slenderness at ambient temperature, in carbon and stainless steel material

Source: created by the author

To assess the suitability of the columns' slenderness limits, the critical loads obtained were normalized by the yield load. The results demonstrate a reduction in N_{cr}/N_{pl} as the nondimensional slenderness increases. The close agreement between the two material curves shows that the buckling behavior is essentially comparable under the same boundary conditions and effective length. For the studied configuration, the structural response is primarily controlled by geometric slenderness rather than material type.

Table 6. presents the analytical values for compressed columns in carbon steel material at elevated temperatures obtained from equations (1) and (2). Table 7 presents the results for compressed columns, but in stainless austenitic steel material

Table 6. Analytical N_{pl} and N_{cr} critical loads at 400, 600 and 800°C in carbon steel material S235

600 and 800 °C in carbon steel material S235				
B, t, mm	L, mm	$\bar{\lambda}_T$	N_{pl}, kN	N_{cr}, kN
T=400°C				
$B=50$ $t=3$	1000	1.32	132.54	75.6
	2000	2.65		18.9
	3000	3.97		8.4
$B=60$ $t=3$	1000	1.09	160.74	134.7
	2000	2.18		33.7
	3000	3.28		15.0
$B=70$ $t=3$	1000	0.93	188.94	218.6
	2000	1.86		54.7
	3000	2.79		24.3
T=600°C				
$B=50$ $t=3$	1000	1.36	62.29	33.5
	2000	2.73		8.4
	3000	4.09		3.7
$B=60$ $t=3$	1000	1.13	75.55	59.7
	2000	2.25		14.9
	3000	3.38		6.6
$B=70$ $t=3$	1000	0.96	88.80	96.8
	2000	1.92		24.2
	3000	2.87		10.8
T=800°C				
$B=50$ $t=3$	1000	1.22	14.58	9.7
	2000	2.45		2.4
	3000	3.67		1.1
$B=60$ $t=3$	1000	1.01	17.68	17.3
	2000	2.02		4.3
	3000	3.03		1.9
$B=70$ $t=3$	1000	0.86	20.78	28.1
	2000	1.72		7.0
	3000	2.58		3.1

Source: created by the author

Figure 3 shows the obtained curves of the Euler critical load in relation to the plastic load vs the non-dimensional slenderness. Both the critical and plastic loads were obtained at 400, 600 and 800 °C.

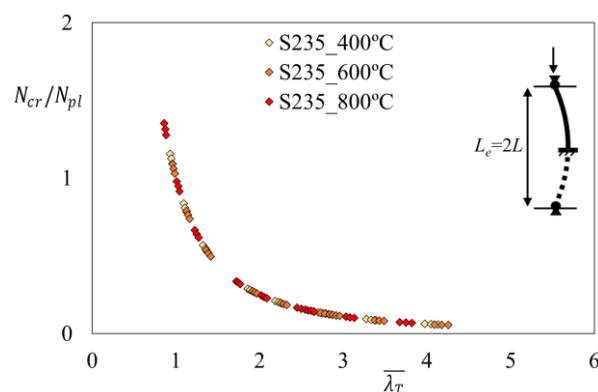


Fig. 3: Critical loads vs. non-dimensional slenderness at elevated temperatures. N_{cr} and N_{pl} , both at elevated temperatures, in carbon steel S235

Source: created by the author

Table 7. Analytical N_{pl} and N_{cr} critical loads at 400, 600 and 800°C in stainless austenitic steel material EN1.4401/1.4404

$B, t, \text{ mm}$	$L, \text{ mm}$	$\bar{\lambda}_T$	$N_{pl}, \text{ kN}$	$N_{cr}, \text{ kN}$
$T=400^{\circ}\text{C}$				
$B=50$ $t=3$	1000	1.19	123.18	86.42
	2000	2.39		21.61
	3000	3.58		9.60
$B=60$ $t=3$	1000	0.99	149.39	153.96
	2000	1.97		38.49
	3000	2.96		17.11
$B=70$ $t=3$	1000	0.84	175.59	249.85
	2000	1.68		62.46
	3000	2.52		27.76
$T=600^{\circ}\text{C}$				
$B=50$ $t=3$	1000	1.18	108.29	78.19
	2000	2.35		19.55
	3000	3.53		8.69
$B=60$ $t=3$	1000	0.97	131.33	139.30
	2000	1.94		34.82
	3000	2.91		15.48
$B=70$ $t=3$	1000	0.83	154.37	226.05
	2000	1.65		56.51
	3000	2.48		25.12
$T=800^{\circ}\text{C}$				
$B=50$ $t=3$	1000	1.04	70.39	64.82
	2000	2.08		16.20
	3000	3.13		7.20
$B=60$ $t=3$	1000	0.86	85.36	115.47
	2000	1.72		28.87
	3000	2.58		12.83
$B=70$ $t=3$	1000	0.73	100.34	187.38
	2000	1.46		46.85
	3000	2.20		20.82

Source: created by the author

Figure 4 shows the results of the Euler critical load in relation to the plastic load vs the non-dimensional slenderness in stainless austenitic steel columns at 400, 600 and 800 °C.

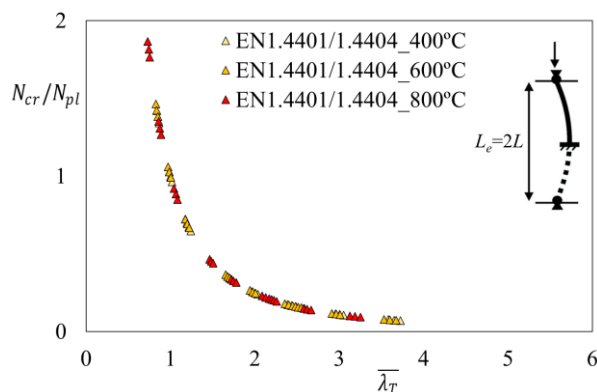


Fig. 4: Critical loads vs. non-dimensional slenderness at elevated temperatures. N_{cr} and N_{pl} , both at elevated temperatures, in stainless austenitic steel material EN1.4401/1.4404

Source: created by the author

Three sets of points are plotted at 400 °C (brown markers), 600 °C (yellow markers), and 800 °C (red markers). These represent different reduction levels in stiffness and yield strength with temperature.

The relation between reduced yield strength and stiffness, given in Tables 1 and 2, is reflected in the behavior shown in Figure 3 and Figure 4.

All three curves show a decreasing trend of N_{cr}/N_{pl} as λ_T increases, reflecting the transition from stocky columns with high load capacity to slender columns governed by elastic buckling.

At low λ_T the ratio is close to or above 1, meaning failure is dominated by plastic or inelastic behavior, whereas at high λ_T the ratio becomes much smaller, indicating strong sensitivity to geometric slenderness and second-order effects.

The fact that carbon steel yield strength in Figure 3 only starts decreasing after 400 °C and then suddenly falls translates into an alternating trend line for N_{cr}/N_{pl} . This relation decreases from 400 °C to 600°C and then drastically increases to 800 °C.

In Figure 4, despite the close agreement between the three temperature curves, the elevated temperature points are slightly above and to the left, confirming the effect of elevated temperature on the buckling resistance of EN1.4401/1.4404.

The main comparisons:

- S235 shows a stronger sensitivity to temperature, with a clearer downward shift in resistance at elevated temperatures;

- EN1.4401/1.4404 keeps the curves more clustered, so that the critical load with the same

temperature variation is higher in the range represented in the graph;

- In both cases, the governing trend is the same: larger λ_T means much lower normalized critical load;

- The difference is mainly in the vertical position of the curves, not in the overall shape.

In column carbon steel, its stiffness and strength degrade more noticeably under fire exposure.

Columns in stainless steel grade EN1.4401/1.4404 retain their buckling capacity better, which is why their curves remain slightly higher and more compact across the temperature levels. In practical terms, the stainless steel column appears to be less affected by temperature increase than the carbon steel one.

5 Conclusion

The buckling of compressed columns at elevated temperatures remains a critical problem in structural stability, as the progressive loss of stiffness and strength accelerates the onset of elastic and inelastic instability. In this study, the comparison between the analytical formulation and the finite element results showed good agreement, with an average relative error of about 6.73%, which supports the validity of the proposed simplified approach for fixed-free square hollow columns.

The results also confirmed that the normalized critical load decreases as thermal slenderness increases, reflecting the transition from stocky members governed mainly by material resistance to slender members controlled by elastic buckling. Carbon steel S235 showed a more pronounced reduction in buckling resistance with temperature, particularly above 400–600 °C, whereas EN1.4401/1.4404 stainless steel retained its capacity more effectively and presented a more stable response across the studied temperature range. The buckling changes from elastic-plastic at ambient temperatures to highly nonlinear, with decreased elastic modulus and yield strength, indicating early buckling and probable failure.

Linear buckling analysis of compressed carbon and stainless steel columns at elevated temperatures shows that stainless steel performs better due to enhanced material retention of stiffness.

Comparing the results, both materials exhibit a similar decrease in normalized critical load with increasing thermal slenderness. However, S235 shows a more visible reduction in buckling resistance at elevated temperatures, whereas EN1.4401/1.4404 presents a more stable response, with the three temperature curves remaining closer.

Overall, the study demonstrates that finite element analysis can serve as a practical complement to the analytical formulation in estimating the buckling response of compressed columns at elevated temperatures. The proposed calibration factor provides a useful basis for direct calculations, although its applicability should be further verified for other geometries, imperfection amplitudes, and boundary conditions.

As future work, the numerical model will incorporate geometric imperfections and material nonlinearity, leading to unified behaviors of the columns, with the calibration of design reduction factors in stability solutions, allowing for the development of parametric sensitivity analyses and assertions about the shortcomings of Eurocode formulations. Additionally, non-uniform temperature fields will be evaluated, focusing on predicting the strength degradation for partially isolated columns subjected to the standard fire curve.

Acknowledgement:

The author acknowledges Fundação para a Ciência e a Tecnologia (FCT) for its financial support to LAETA via the project UID/50022/2025 (DOI: <https://doi.org/10.54499/UID/50022/2025>).

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

- Conceptualization, E.M.M.F.; methodology, D.A.M.S.; validation, D.A.M.S.; investigation, D.A.M.S.; writing-original draft preparation, D.A.M.S.; writing-review and editing, E.M.M.F.; supervision, E.M.M.F. All authors have read and agreed to the published version of the manuscript.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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