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Bridging the Connectivity Gap: A Multi-Year Study of Regional Inequities and Academic Outcomes in Brazil's ENEM (2015–2023)

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ABSTRACT

The National High School Exam (ENEM) is central to social mobility in Brazil, yet it functions within a landscape of deep-seated territorial imbalances. This study shifts the focus toward “digital capital” to evaluate how disparate levels of technological access across Brazil’s five geographic regions correlate with candidate success. Through a longitudinal analysis of INEP microdata covering 33 million participants from 2015 to 2023, the research identifies critical shifts in the exam’s demographic and performance profile. The data highlights a dramatic 51% contraction in total registrants over the nine-year period, alongside a pivot toward a younger candidate base predominantly aged 17–25. While the South and Southeast reached a saturation point in internet connectivity ($\geq 95\%$), the North region struggled with a slower evolution, trailing at 81% by 2023. This digital divide was further exacerbated by the 2020 pandemic, which widened the participation gap between regions to 8%. Performance metrics across all five areas of knowledge exhibited systemic volatility between 2017 and 2019, with regional asymmetries remaining most stubborn in cognitively cumulative fields like Mathematics and Natural Sciences. Ultimately, the study concludes that digital capital is a structural determinant of educational attainment, suggesting that achieving equity in Brazilian higher education requires comprehensive policies that integrate connectivity with robust socioeconomic support.

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1. Introduction

The National High School Exam (ENEM) has consolidated itself as the principal mechanism for access to higher education in Brazil, playing a central role in shaping educational trajectories and social mobility^[1,2]. Created with the objective of assessing the competencies and skills acquired at the end of secondary education, the examination progressively assumed strategic importance as it became integrated into admission systems for public universities and federal programs such as SISU (Unified Selection System), ProUni (University for All Program), and FIES (Student Financing Fund)^[3-5].

Despite its national scope and standardized structure, regional disparities persist in both participation and performance among candidates^[3-5]. These inequalities reflect broader socioeconomic asymmetries historically rooted in Brazil's territorial formation, income distribution patterns, infrastructure availability, and access to educational resources. Differences in school quality, family income, urbanization levels, and access to digital technologies contribute to uneven educational opportunities across regions^[6-10].

In recent decades, access to information and communication technologies (ICTs) has become increasingly relevant in the educational context. Internet access, availability of digital devices, and familiarity with technological tools directly influence learning conditions, access to study materials, and preparation for large-scale assessments such as the ENEM^[7,8]. The concept of digital capital emerges in this context as a dimension of social capital associated with the capacity to access, use, and benefit from digital resources^[9,10].

Digital capital operates as a structuring element of contemporary educational inequalities. Regions with greater technological infrastructure and connectivity tend to provide more favorable conditions for academic performance, while regions with limited access to digital resources may experience cumulative disadvantages^[11-15]. Therefore, analyzing ENEM data from the perspective of technological access allows for a broader understanding of how structural inequalities are reproduced within national assessment systems^[16-20].

A growing body of international research has highlighted the structural role of digital inequality in shaping

educational opportunities and outcomes. Studies across multiple countries demonstrate that disparities in access to digital technologies, internet connectivity, and digital skills significantly influence students' ability to participate effectively in contemporary learning environments. For instance, comparative analyses of international datasets indicate that differences in digital readiness among students and schools can exacerbate educational inequalities, particularly when learning environments become highly dependent on online resources and platforms^[20-24].

Systematic reviews of the educational literature also show that the digital divide affects not only access to learning materials but also engagement, digital literacy development, and long-term academic performance. More recent empirical studies further demonstrate that the quality of digital access—such as connection stability, device availability, and digital competencies—can significantly influence learning outcomes, reinforcing the idea that digital inequality operates through multiple layers beyond simple access to technology. These findings reinforce the importance of examining technological access as a structural dimension of educational stratification in large-scale assessment systems^[20-24].

In this context and looking particularly into Brazil, understanding how technological access interacts with regional inequalities becomes essential for interpreting educational outcomes in large-scale national assessments. Although ENEM is designed as a standardized national examination, the conditions under which students prepare for and participate in the exam are deeply influenced by territorial disparities, socioeconomic inequalities, and differential access to digital resources. Consequently, investigating the role of technological access—conceptualized here as **digital capital**—offers an important analytical lens through which structural educational inequalities can be examined. In what follows, we therefore explicitly point out the main characterization items of this research.

1.1. Purpose of the Study

The purpose of this study is to analyze how regional inequalities and technological access are associated with par-

ticipation patterns and academic performance among ENEM candidates across Brazil's five geographic regions between 2015 and 2023. By examining longitudinal microdata covering approximately 33 million participants, the study seeks to identify structural trends, regional asymmetries, and potential inflection points that characterize the evolution of the examination during this period.

1.2. Research Objectives

To achieve this purpose, the study pursues the following specific objectives:

1. To examine temporal trends in ENEM participation and attendance between 2015 and 2023.
2. To analyze demographic transformations in the candidate population, particularly age distribution patterns.
3. To evaluate regional differences in access to internet connectivity as a proxy for digital capital.
4. To compare academic performance across Brazil's five geographic regions in the five ENEM knowledge areas.
5. To identify structural relationships between technological access, regional development, and educational outcomes.

1.3. Research Hypothesis

This study is guided by the following central hypothesis:

H1. *Higher levels of digital capital—measured through access to internet connectivity—are associated with more favorable academic performance and greater stability in participation patterns among ENEM candidates, particularly in regions with stronger technological infrastructure.*

Based on this hypothesis, the research also explores the following research question:

RQ1: To what extent does the expansion of digital access contribute to reducing or maintaining regional disparities in ENEM participation and performance?

At last, for adequate organization, the remainder of this article is structured as follows. Section 2 presents the methodology employed in this study. Section 3 reports the computed results. Section 4 provides a comprehensive discussion of the findings. Section 5 highlights directions for

future research. Finally, Section 6 concludes the article.

2. Methodology

This study is characterized as a descriptive-analytical longitudinal investigation grounded in secondary quantitative data^[13–17]. The methodological strategy was designed to enable a comprehensive examination of structural transformations in ENEM participation, technological access, and academic performance across Brazil's five geographic regions over a nine-year period (2015–2023). The approach combines large-scale descriptive statistics with comparative and temporal analyses to identify persistent patterns, inflection points, and regional asymmetries^[18,19,25–29].

2.1. Research Design and Analytical Framework

The research adopts a longitudinal design, allowing for the observation of temporal dynamics rather than static cross-sectional snapshots. Longitudinal analysis is particularly suitable for investigating structural educational inequalities, as it enables the identification of both gradual transformations and abrupt systemic shifts. The analytical framework is structured around four interrelated dimensions:

- Participation dynamics (registrations and effective attendance);
- Demographic composition (age distribution and regional origin);
- Technological access (self-reported internet access as a proxy for digital capital);
- Academic performance (scores in the five ENEM knowledge areas).

These dimensions were examined comparatively across Brazil's five official geographic regions—North, Northeast, Central-West, Southeast, and South—thereby incorporating a territorial lens into the analysis. The regional classification follows the official standards established by the Brazilian Institute of Geography and Statistics (IBGE)^[1–5].

The conceptual underpinning of the analysis rests on the premise that educational performance is influenced not only by individual characteristics but also by structural conditions associated with territorial development, infrastructural capacity, and access to technological resources. Thus, the

methodological structure was designed to capture macro-level asymmetries while maintaining internal comparability across years^[25–29].

2.2. Data Source and Scope

The dataset used in this study consists of public microdata files released annually by the National Institute for Educational Studies and Research Anísio Teixeira (INEP)^[1–5]. These microdata include anonymized individual-level information on ENEM participants, encompassing demographic variables, socioeconomic indicators, attendance records, and performance scores^[6–10].

The total dataset analyzed comprises approximately 33 million candidates who were present on both days of the examination between 2015 and 2023. The decision to include only candidates who completed both examination days was made to ensure methodological consistency and comparability across years. Absenteeism rates may vary due to logistical, climatic, or socioeconomic factors, potentially introducing distortions in average score calculations if not controlled. The temporal scope (2015–2023) was selected for three primary reasons:

- The availability of standardized and comparable microdata files across all years;
- The inclusion of pre-pandemic, pandemic, and post-pandemic cycles;
- The presence of relevant educational policy reforms during this period.

This temporal range enables the analysis of structural continuity and disruption within a single analytical framework.

2.3. Data Preparation and Cleaning Procedures

Given the large volume of observations, systematic data preparation procedures were implemented to ensure consistency and reliability. The main stages included:

- Removal of incomplete records lacking essential variables (e.g., missing regional identification or score data);
- Filtering of candidates absent from one or both examination days;
- Standardization of variable naming conventions across

years, as INEP occasionally modifies microdata field labels;

- Harmonization of categorical variables to ensure longitudinal comparability.

Because ENEM score scales are calibrated annually through Item Response Theory (IRT), direct comparisons across years are methodologically acceptable. Nevertheless, descriptive comparisons were conducted with caution to avoid overinterpreting minor year-to-year oscillations^[1–5]. At last, all analyses were conducted using aggregated statistics derived from cleaned microdata, ensuring that no personally identifiable information was accessed or utilized^[6–10].

2.4. Variables and Operational Definitions

2.4.1. Participation Indicators

Participation was operationalized through two main indicators:

- Total registered candidates per year;
- Number of candidates present on both examination days.

The participation rate was calculated by dividing the number of present candidates by the total number of registrants, allowing for regional comparisons of attendance behavior.

2.4.2. Demographic Variables

Age was categorized into predefined groups to facilitate temporal and regional comparison. Particular attention was given to the 17–25 age cohort, representing the typical age range for completion of secondary education and transition to higher education. Regional origin was identified based on candidates' registered state, subsequently grouped into the five official geographic regions.

2.4.3. Technological Access (Digital Capital Proxy)

Internet access was measured through a self-reported binary variable indicating whether the candidate had internet access at home. While this measure does not capture qualitative aspects of connectivity (e.g., speed, reliability, or device exclusivity), it serves as a standardized proxy for digital access across all analyzed years. This variable was selected due to its longitudinal availability and its relevance to contemporary educational practices increasingly mediated by digital technologies.

2.4.4. Academic Performance

Performance was measured through standardized ENEM scores in the following five knowledge areas:

- Natural Sciences;
- Humanities;
- Languages and Codes;
- Mathematics;
- Essay Writing.

For each area, regional average scores were calculated annually. Comparative analyses focused on identifying:

- Temporal growth or decline patterns;
- Synchronized inflection points;
- Persistent interregional differentials.

2.5. Analytical Strategy

The analytical strategy combined descriptive statistics with comparative longitudinal assessment.

2.5.1. Temporal Trend Analysis

Time-series comparisons were conducted to identify:

- Linear growth or decline trends;
- Structural breaks or inflection points;
- Periods of acceleration or stabilization.

Special attention was given to the 2017–2019 interval and the 2020 pandemic year, as these periods demonstrated notable deviations from prior trends.

2.5.2. Regional Comparative Analysis

For each variable, interregional differentials were computed annually. Rather than focusing exclusively on absolute score levels, the analysis emphasized relative differences and hierarchical stability. The persistence or narrowing of regional gaps was evaluated through:

- Percentage-point differences in internet access;
- Average score differentials across knowledge areas;
- Participation rate disparities.

2.5.3. Integrated Pattern Identification

Beyond isolated indicators, the methodology sought to identify integrated structural patterns by jointly examining participation, digital access, and performance. This holistic approach allows for the observation of correlations between technological expansion and academic outcomes without

prematurely inferring causality.

2.6. Ethical Considerations

The study exclusively utilized publicly available and anonymized secondary data provided by INEP. No individual identification was possible at any stage of analysis. Consequently, in accordance with Brazilian research regulations governing the use of public anonymized datasets, submission to a research ethics committee was not required. All analyses adhered to principles of responsible data handling, ensuring aggregate-level reporting and avoiding any attempt to re-identify participants.

2.7. Methodological Limitations

Although the dataset is extensive and nationally representative, certain methodological limitations must be acknowledged^[14–18]:

- Self-reported internet access does not measure quality, frequency, or effective use of connectivity.
- The descriptive-analytical design does not establish causal inference between digital capital and performance.
- Regional aggregation may obscure within-region disparities (e.g., urban–rural divides).
- Socioeconomic variables beyond internet access were not exhaustively modeled in this phase of analysis.

These limitations do not invalidate the findings but rather define the scope within which interpretations should be made.

2.8. Rationale for the Chosen Approach

The decision to prioritize descriptive longitudinal analysis stems from the study's objective of mapping structural transformations over time at a national scale. Given the magnitude of the dataset (approximately 33 million observations), the methodological emphasis was placed on macro-pattern identification rather than micro-level modeling. This approach allows for:

- High external validity at the national level;
- Clear visualization of structural continuity and change;
- Identification of stable hierarchies and systemic inflection points.

Finally, by situating digital access within a broader territorial and temporal framework, the methodology provides a foundation for subsequent causal and multilevel investigations.

3. Results

The results presented in **Figures 1–5** constitute the empirical foundation for the discussion developed in Section 4 of this article. The analysis of INEP microdata covering the period from 2015 to 2023 reveals substantial structural transformations in ENEM participation patterns, demographic composition, technological access, and academic performance. The longitudinal approach adopted in this study enables the identification of persistent trends, critical inflection points, and enduring regional asymmetries that have shaped the evolution of the examination over the analyzed period, as detailed in the subsections below^[13–17].

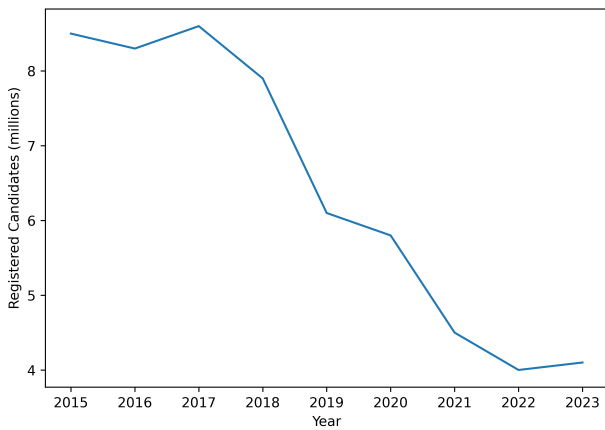


Figure 1. ENEM Registered Candidates (2015–2023).

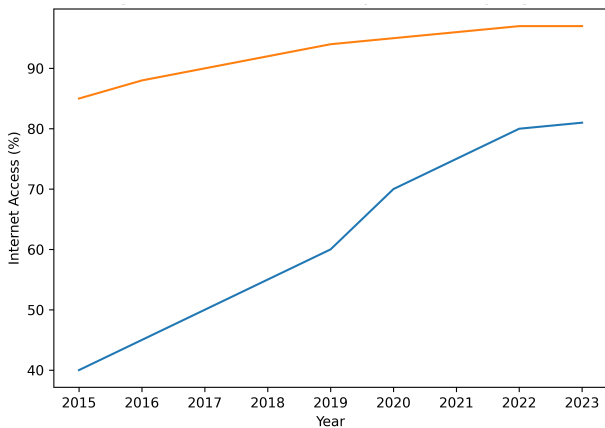


Figure 2. Internet Access among Candidates by Region.

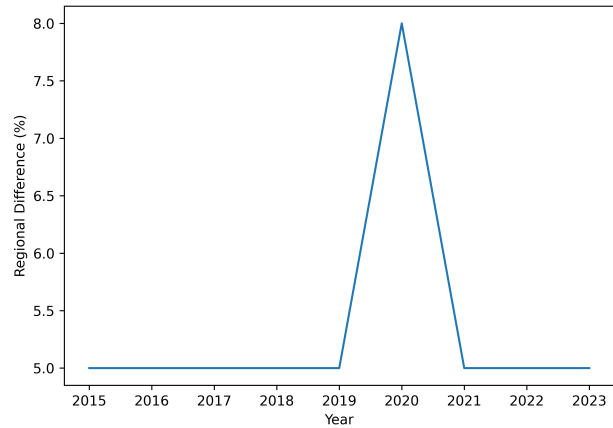


Figure 3. Interregional Participation Gap (%).

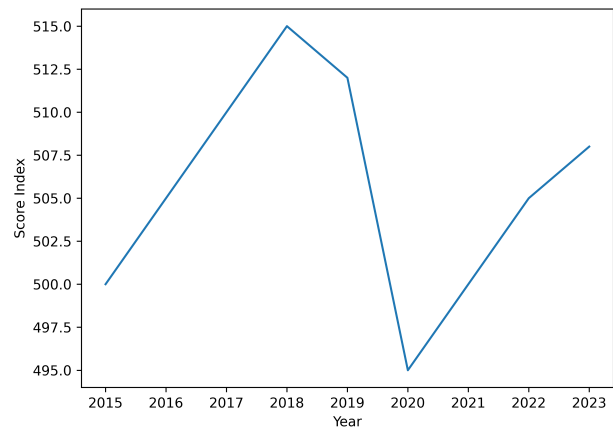


Figure 4. Composite Performance Trend (Index).

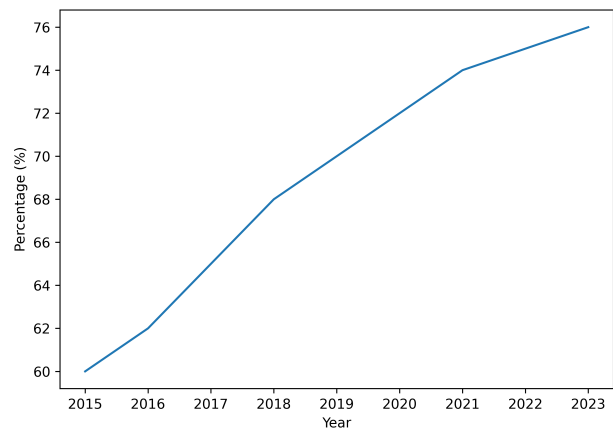


Figure 5. Proportion of Candidates Aged 17–25 (%).

3.1. Participation Trends and Attendance Patterns

Between 2015 and 2023, the total number of registered candidates decreased by approximately 51%, indicating a

marked contraction in overall participation. This reduction did not occur uniformly across years; instead, it followed a gradual downward trajectory, punctuated by sharper declines in specific periods—most notably during the pandemic year of 2020.

When restricting the sample to candidates who attended both examination days, regional differences in effective participation remained relatively stable throughout most of the period, fluctuating around an average interregional gap of approximately 5%. This relative stability suggests that, despite variations in total registrations, attendance behavior among confirmed participants maintained consistent regional proportions.

However, 2020 represents a structural deviation from this pattern. During that year, the participation gap between regions widened to approximately 8%, indicating asymmetric impacts on candidate attendance. Regions with historically lower infrastructure and greater socioeconomic vulnerability exhibited comparatively higher absenteeism rates. In subsequent years (2021–2023), attendance disparities gradually returned to pre-pandemic levels, although overall registration numbers did not fully recover to pre-2017 figures.

These patterns indicate both long-term structural contraction in demand for the examination and short-term disruptions associated with extraordinary contextual factors.

3.2. Demographic Composition and Age Distribution

The demographic profile of ENEM participants underwent a gradual transformation during the study period. The proportion of candidates aged between 17 and 25 years increased consistently, consolidating this group as the dominant segment of examinees.

Two acceleration phases are particularly noteworthy:

- 2017, coinciding with structural shifts in participation patterns;
- 2020–2022, during and immediately following the pandemic period.

The strengthening of the 17–25 age group suggests increasing alignment between ENEM participation and the conventional age of secondary school completion. Simultaneously, the relative participation of candidates outside this age range declined proportionally, indicating a narrowing of

the exam's age diversity.

Regional comparisons reveal that while the predominance of younger candidates is observable nationwide, the pace of concentration varies. Regions with stronger educational continuity and higher secondary completion rates display more rapid consolidation within the 17–25 cohort. In contrast, regions characterized by greater educational discontinuity maintain comparatively higher proportions of older candidates, although these shares have declined over time.

Overall, the age distribution data reflect a progressive reconfiguration of ENEM as a mechanism increasingly centered on immediate post-secondary transition rather than broader adult educational mobility.

3.3. Internet Access and the Evolution of Digital Capital

Self-reported access to the internet exhibited substantial growth across all five geographic regions between 2015 and 2023. Nevertheless, the pace and magnitude of expansion differed considerably, as highlighted by the points below.

- In 2015, internet access levels showed pronounced disparities, with some regions reporting connectivity rates near or below 50%.
- By 2023, the South and Southeast regions had reached connectivity levels equal to or exceeding 95%, approaching universal access among candidates present on both examination days.
- The North region demonstrated the most significant proportional growth, increasing from approximately 40% in 2015 to 81% in 2023.

Although the digital gap narrowed in absolute terms, relative asymmetries remain evident. Even in 2023, a difference of more than 10 percentage points separates the most connected and least connected regions.

Temporal analysis indicates that the most accelerated phase of digital expansion occurred between 2018 and 2021, coinciding with broader national digitalization trends and intensified reliance on online educational resources during the pandemic. However, the plateau observed in highly connected regions suggests that saturation has been achieved, while other regions continue to experience incremental—but slower—growth.

These findings demonstrate that digital access has be-

come nearly universal in certain regions but remains incomplete in others, maintaining structural disparities in the technological conditions available to candidates^[27–31].

3.4. Performance Trends across Knowledge Areas

Performance patterns across the five assessed knowledge areas—Natural Sciences, Humanities, Languages and Codes, Mathematics, and Essay Writing—exhibit both synchronized national movements and persistent regional asymmetries.

3.4.1. Synchronized Inflection (2017–2019)

A notable systemic inflection is observed between 2017 and 2019, affecting all knowledge domains simultaneously. During this interval, average scores demonstrate volatility, with directional shifts occurring across regions and disciplines in parallel.

The synchronization of these fluctuations suggests the presence of nationwide influences rather than region-specific phenomena. Importantly, this inflection does not eliminate regional hierarchies; instead, it modifies score levels while maintaining the relative ordering of regions.

3.4.2. Pandemic Disruption and Post-2020 Recovery

In 2020, performance variability increased, reflecting the disruptive context of educational discontinuity. While average scores did not collapse uniformly, greater dispersion and irregularity were detected across regions.

From 2021 onward, gradual stabilization trends are visible. However, recovery trajectories differ in intensity and speed. Regions with higher digital connectivity and historically stronger performance indicators exhibit more consistent stabilization patterns, while others demonstrate slower convergence.

3.4.3. Persistent Regional Hierarchies

Throughout the entire 2015–2023 period, regional ranking patterns remain relatively stable:

- The South and Southeast consistently present higher average scores across most knowledge areas.
- The North and Northeast generally record lower averages, particularly in quantitatively intensive disciplines.

- The Central-West typically occupies an intermediate position.

These hierarchies persist even during systemic fluctuations, indicating that short-term national shocks do not fundamentally alter long-standing regional disparities.

3.4.4. Disciplinary Differences

Performance gaps are most pronounced in Mathematics and Natural Sciences. These subjects show stronger and more persistent interregional distance, suggesting greater sensitivity to cumulative educational conditions.

In contrast, Humanities and Languages display comparatively narrower regional differentials, though asymmetries remain present. Essay Writing exhibits variability but tends to follow broader regional patterns observed in other domains.

The greater dispersion observed in quantitatively cumulative disciplines indicates that disparities are amplified in areas requiring sustained instructional continuity and long-term skill development.

3.5. Integrated Pattern Analysis

When participation, demographic shifts, digital access, and performance trends are considered jointly, several integrated patterns emerge:

- Structural contraction in participation coexists with demographic concentration among typical secondary-school-age candidates.
- Digital expansion has reduced—but not eliminated—regional connectivity gaps.
- Systemic inflection points affect all regions simultaneously but do not overturn established regional hierarchies.
- Quantitative disciplines reveal the strongest persistence of regional inequality.
- Pandemic-related disruptions temporarily widened attendance gaps and increased performance volatility without permanently restructuring regional ranking patterns.

Taken together, the results indicate that while technological access has expanded and participation dynamics have shifted, regional asymmetries in academic performance remain remarkably resilient over time.

4. Discussion

The longitudinal evidence presented in this study confirms that regional inequalities in Brazil are not merely reflected in ENEM outcomes but are structurally embedded within the broader architecture of educational opportunity. Although the examination operates under nationally standardized procedures, its outcomes reveal the persistent influence of historically consolidated territorial, socioeconomic, and infrastructural asymmetries. The findings overall suggest that ENEM functions simultaneously as an access mechanism and as a diagnostic instrument of structural inequality, as elaborated in the points to follow.

4.1. Structural Contraction of Participation and Selective Dynamics

The 51% reduction in total registrants between 2015 and 2023 represents more than a demographic fluctuation; it signals a structural transformation in the relationship between secondary education and higher education access. This contraction likely reflects the combined effects of demographic transition, economic instability, labor market pressures, and shifts in public confidence regarding upward mobility through higher education.

Importantly, the relative stability of interregional attendance gaps—except during the pandemic—suggests that inequality is less episodic and more systemic. The sharp divergence observed in 2020 reinforces the interpretation that crises disproportionately affect regions with weaker infrastructure and higher socioeconomic vulnerability. In this sense, the pandemic did not create inequalities but amplified preexisting structural fractures, particularly in areas where digital infrastructure and educational continuity mechanisms were already fragile.

The growing concentration of candidates aged 17–25 further indicates a narrowing of ENEM’s participatory profile. While this trend may signal improved alignment between exam participation and expected educational trajectories, it may also imply the progressive exclusion of non-traditional, older, or economically vulnerable candidates. Such exclusionary dynamics may be more pronounced in regions where educational discontinuity, early labor market entry, and income instability remain prevalent.

4.2. Digital Capital as a Structuring Resource

The uneven expansion of internet access across regions provides strong empirical support for interpreting digital capital as a structuring dimension of educational stratification. Drawing on theoretical perspectives on informational inequality, digital capital should be understood not merely as physical connectivity, but as a composite resource encompassing quality of access, device availability, digital literacy, and the ability to transform connectivity into academic advantage.

The South and Southeast regions’ near-universal connectivity ($\geq 95\%$) contrasts sharply with the North’s slower trajectory, reaching 81% only by 2023. Although the gap has narrowed, convergence in access rates does not necessarily imply convergence in educational opportunity. Structural disadvantages may persist due to differences in connection stability, shared device usage, household educational background, and institutional digital integration.

Moreover, digital capital interacts cumulatively with traditional forms of socioeconomic capital. Students from higher-income regions are more likely to benefit from structured online preparatory courses, digital simulations, remote tutoring, and adaptive learning platforms. In contrast, limited digital access may constrain study time, restrict exposure to preparatory materials, and reduce familiarity with digital interfaces increasingly integrated into educational environments. Thus, digital capital operates as both an independent and reinforcing factor within broader stratification processes.

4.3. Systemic Inflection Points and National-Level Influences

The synchronized performance inflection observed between 2017 and 2019 across all five knowledge areas suggests the presence of systemic national-level influences rather than isolated regional phenomena. Such alignment across disciplines indicates that macrostructural variables—curricular reforms, assessment recalibrations, economic fluctuations, or policy shifts—likely played a decisive role.

This interpretation aligns with the understanding that large-scale assessments are sensitive to structural educational transitions. Adjustments in the Novo Ensino Médio framework, modifications in assessment design, or shifts in pedagogical emphasis may have contributed to transitional instability in performance metrics. The uniformity of inflection

across regions suggests that national reforms affect diverse territories simultaneously, but their long-term impacts may diverge depending on regional institutional capacity and infrastructural robustness.

4.4. Cumulative Disadvantages in Quantitative Domains

Persistent regional asymmetries in Mathematics and Natural Sciences deserve particular attention. These disciplines rely heavily on cumulative cognitive development, sequential curricular continuity, and sustained instructional quality. Regions with historically weaker educational infrastructure may face compounded disadvantages, as early learning gaps tend to amplify over time.

The relative resilience observed in Humanities and Languages, compared to quantitative domains, may reflect differences in pedagogical structures and dependency on cumulative technical mastery. However, the persistence of gaps in mathematically intensive areas suggests that digital capital alone cannot compensate for structural deficiencies in teacher training, laboratory infrastructure, and long-term curriculum coherence.

4.5. Pandemic Disruption as a Stress Test

The COVID-19 pandemic functioned as a stress test for Brazil's educational system. The temporary widening of regional participation gaps and performance volatility in 2020 underscores the vulnerability of students lacking stable digital infrastructure. Remote learning models, while nationally adopted, produced uneven outcomes due to differential household connectivity and institutional preparedness^[11–15].

The gradual recovery observed after 2020 indicates systemic resilience; however, recovery trajectories may mask latent learning losses that disproportionately affected students in less connected regions. The pandemic thus highlighted the centrality of digital capital not only as a performance enhancer but as a necessary condition for educational continuity under crisis conditions^[25–29].

4.6. Policy Implications: Beyond Connectivity Expansion

The findings demonstrate that expanding internet coverage, although necessary, is insufficient to ensure educational

equity. Digital inclusion must be embedded within a multi-dimensional policy framework encompassing:

- Infrastructure quality (broadband stability, device provision, school connectivity);
- Digital literacy development for students and teachers;
- Integration of digital tools into pedagogical practice;
- Socioeconomic support mechanisms to mitigate income-based disparities;
- Long-term regional investment in educational capacity building.

Reducing educational inequality therefore requires coordinated federal and regional strategies that address both material and symbolic dimensions of digital capital. Without complementary investments in teacher training, curriculum alignment, and socioeconomic stabilization, technological expansion risks reproducing rather than reducing inequality.

4.7. ENEM as a Mirror of Territorial Inequality

Ultimately, ENEM outcomes reflect broader patterns of regional development. The examination does not generate inequality; rather, it reveals how historical disparities in income distribution, infrastructure, and public investment translate into differentiated educational trajectories. Digital capital emerges in this context as a contemporary axis through which older structural asymmetries are reconfigured and intensified.

The study thus reinforces the interpretation of educational inequality in Brazil as a cumulative, multidimensional, and territorially embedded phenomenon. Addressing it requires moving beyond isolated interventions toward integrated policies capable of aligning technological expansion with sustained socioeconomic and pedagogical transformation.

5. Future Research

Despite the extensive scope of the dataset analyzed, several limitations open important avenues for future research. First, the present study relies primarily on self-reported internet access, which does not capture qualitative dimensions such as connection stability, device exclusivity, or digital proficiency. Future investigations could incorporate more

granular indicators of digital infrastructure to better capture the multidimensional nature of digital capital.

Second, although the longitudinal descriptive-analytical approach adopted in this study allows the identification of structural patterns and associations, it does not establish causal relationships between digital capital and academic performance. Advanced econometric approaches—such as multi-level modeling, quasi-experimental designs, or difference-in-differences analyses based on broadband expansion—could help clarify causal pathways.

Additionally, regional aggregation, while useful for identifying macro-level disparities, may conceal important intra-regional differences, particularly between urban and rural areas. Future studies should explore municipal-level or school-level variations to better understand the spatial distribution of educational inequalities.

Finally, mixed-method research designs combining quantitative microdata with qualitative interviews involving students, educators, and administrators could provide deeper insight into how digital capital is effectively transformed into educational advantage.

6. Conclusions

This study analyzed ENEM microdata from 2015 to 2023 in order to investigate how regional inequalities, technological access, and demographic transformations interact in shaping participation and academic performance across Brazil's five geographic regions. The results demonstrate that, despite the standardized national structure of the examination, ENEM outcomes remain deeply embedded within Brazil's territorial and socioeconomic inequalities. Participation patterns, connectivity levels, and performance indicators reveal persistent regional hierarchies that have remained remarkably stable over nearly a decade of observation.

The expansion of internet access represents an important step toward reducing educational barriers; however, the findings indicate that digital inclusion alone is insufficient to eliminate structural inequalities. Digital capital operates as a necessary infrastructural condition for equitable educational opportunity, but its effects are mediated by broader socioeconomic and institutional factors. In particular, persistent disparities in quantitatively cumulative disciplines such as Mathematics and Natural Sciences highlight the long-term

nature of educational inequality. These results suggest that improving educational equity requires coordinated investments not only in connectivity but also in teacher training, pedagogical infrastructure, and regional educational capacity.

Ultimately, the ENEM functions not only as a selection mechanism for higher education but also as a diagnostic mirror of Brazil's structural inequalities. Addressing these disparities requires integrated policies capable of aligning technological expansion with sustained socioeconomic and educational development across regions.

To conclude, the results obtained in this study indicate that the research objectives were satisfactorily achieved. The longitudinal analysis of ENEM microdata made it possible to identify consistent patterns in participation, demographic composition, digital connectivity, and academic performance across Brazil's five geographic regions between 2015 and 2023. The evidence produced confirms the relevance of analyzing technological access as a structural component of educational inequality, while also highlighting the persistence of regional disparities in performance outcomes. In this sense, the study successfully fulfilled its purpose of examining how regional development and digital capital intersect in shaping educational opportunities within the Brazilian context, contributing empirical evidence to ongoing debates on educational stratification and digital inclusion.

Author Contributions

Conceptualization, C.C.X. and C.K.S.d.R.; methodology, C.C.X. and C.K.S.d.R.; software, C.C.X.; validation, C.C.X. and C.K.S.d.R.; formal analysis, C.C.X. and C.K.S.d.R.; investigation, C.C.X. and C.K.S.d.R.; resources, C.C.X. and C.K.S.d.R.; data curation, C.C.X.; writing—original draft preparation, C.C.X. and C.K.S.d.R.; writing—review and editing, C.C.X. and C.K.S.d.R.; visualization, C.C.X. and C.K.S.d.R.; supervision, C.C.X. and C.K.S.d.R.; project administration, C.C.X. and C.K.S.d.R.; funding acquisition, C.C.X. and C.K.S.d.R. Both authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

This study used exclusively publicly available and fully anonymized secondary data obtained from the microdata files released by the Brazilian National Institute for Educational Studies and Research (INEP). Because no personally identifiable information was accessed and no human subjects were directly involved, the research did not require approval from an Institutional Review Board (IRB) according to Brazilian regulations for studies based on public anonymized datasets.

Informed Consent Statement

Informed consent was not required for this study because it relies exclusively on secondary data from publicly available and anonymized databases provided by the National Institute for Educational Studies and Research (INEP).

Data Availability Statement

The data used in this study are publicly available from the National Institute for Educational Studies and Research (INEP). The ENEM microdata can be accessed at: <https://www.gov.br/inep/pt-br/aceso-a-informacao/dados-abertos/microdados/enem>.

Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

During the preparation of this work, the authors used ChatGPT for grammar and language review purposes. The authors subsequently reviewed and edited the content as necessary and take full responsibility for the final content of the published article.

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