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Infrastructure as Active Mediation: Techno-pedagogical Ecosystems and Teacher Technology Appropriation in Pernambuco State Educational System

Thyago José Oliveira Costa [**Universidade Federal Rural de Pernambuco** | ***thyagojcosta@gmail.com***]
Rodrigo Lins Rodrigues [**Universidade Federal Rural de Pernambuco** | ***rodrigo.linsrodrigues@ufrpe.br***]
Taciana Pontual Falcão [**Universidade Federal Rural de Pernambuco** | ***taciana.pontual@ufrpe.br***]

Department of Computing, Universidade Federal Rural de Pernambuco, Rua Dom Manuel de Medeiros, s/n - Dois Irmãos, Recife - PE, 52171-900, Brazil.

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Abstract The integration of Information and Communication Technologies (ICT) in basic education, driven by uniform policies, often overlooks the heterogeneity of school contexts and how different infrastructures mediate teacher technology appropriation. A critical gap remains concerning how distinct infrastructural configurations shape appropriation processes and adaptive strategies in contexts of material inequality. We conducted an exploratory qualitative comparative study with 25 teachers across three urban schools from Pernambuco state educational system, Brazil, representing distinct infrastructural configurations. A framework analysis was used for structured comparison, generating a provisional typology of three qualitatively distinct techno-pedagogical ecosystems: Survival, Limited Adequacy, and Competition. Results suggest a functional inversion where stable connectivity was perceived by teachers as a more critical conversion factor than equipment quantity. In these ecosystems, infrastructure appears to operate as an active mediator that shapes, but does not determine, pedagogical possibilities. Teachers develop diverse adaptive strategies, including techno-pedagogical bricolage, temporal orchestration, and selective technology appropriation, that complicate simple dichotomies between uncritical adoption and resistance. The discursive appropriation of Artificial Intelligence (AI) manifests differently across these contexts: in contexts of greater adequacy, teachers articulated pragmatic ambivalence (the simultaneous recognition of potentialities and risks alongside functional experimentation) whereas in contexts of scarcity, discourses of technological optimism with limited explicit engagement with risks predominated; these contrasting patterns may also reflect differences in professional development exposure and group discourse norms. Digital citizenship education remains fragmented across all three settings, further highlighting the qualitatively unequal pedagogical possibilities associated with different infrastructural configurations. These provisional findings point toward the need for differentiated public policies that move beyond uniform solutions and recognize teacher agency without romanticizing structural precarity.

Keywords: ICT in Education, Teacher Technology Appropriation, School Infrastructure, Techno-pedagogical Ecosystems, Teacher Education, Educational Policies

1 Introduction

The integration of Information and Communication Technologies (ICT) in Brazilian basic education is marked by tensions between modernization discourses and challenging structural realities [Pretto *et al.*, 2013]. Despite advances in connectivity, with 96% of Brazilian schools having internet access in 2024 [CETIC.BR, 2025], significant structural obstacles persist. For instance, only 59% of schools have both computers and Internet access available for student use, with an average of 24 students per computer (reaching 29 in municipal schools) [CETIC.BR, 2025]. However, aggregate quantitative indicators such as student-to-computer ratios offer limited insight into pedagogical realities: schools with unfavorable ratios may develop effective practices without technology, while schools with substantially more favorable ratios — as the three cases examined in this study illustrate — may face qualitative inadequacies involving connectivity stability, temporal constraints, and functional accessibility that numerical indicators fail to capture. Studies have documented that the mere provision of equipment does not guarantee substantive pedagogical transformations, necessitating an approach that articulates infrastructure, teacher education, and institutional culture [Zhao and Frank, 2003; Pischetola and Miranda, 2020].

The inadequacy of teacher education in ICT is a particularly critical dimension of this scenario. Teacher education for the pedagogical use of technologies remains structurally fragmented [Gatti *et al.*, 2019], with existing programs often evaluated as decontextualized and unable to meet the diverse needs of the classroom [CETIC.BR, 2025; Gatti *et al.*, 2019; Cardoso *et al.*, 2021]. Current data indicate that 54% of teachers received in-service training in the last 12 months [CETIC.BR, 2025], though the adequacy and contextualization of these offerings remain a more critical concern than participation rates alone. In this context, teachers predominantly develop technology appropriation skills through self-teaching, using informal sources such as online tutorials and peer networks [CETIC.BR, 2025]. The interplay between inadequate teacher education, infrastructural inequality, and teacher technology appropriation remains insufficiently understood, demanding theoretical frameworks that can capture this systemic complexity.

Brazilian researchers have developed their own ecological perspectives to analyze educational technology, grounded in media ecology [Pischetola and Miranda, 2020], critical pedagogy [Pretto, 2022], and socio-historical theory [Astudillo and Martín-García, 2020]. These perspectives share a core analytical orientation: rather than treating technologies as isolated inputs, they examine how infrastructure, institutional culture, and teacher education constitute interdependent systems that collectively shape — and constrain — pedagogical possibilities. This study articulates these national perspectives with international ecological approaches that analyze educational technologies as innovations mediated by school ecosystems [Zhao and Frank, 2003]. Within the Pernambuco state educational system, in the northeast of Brazil, individual schools, even when served by common technology provision programs, present qualitatively distinct material conditions in equipment availability, connectivity quality, physical spaces, and institutional support, constituting heterogeneous infrastructural configurations that shape different fields of pedagogical possibilities. This study examines how these configurations mediate teacher technology appropriation in three specific urban contexts.

In Pernambuco, recent investments through coordinated state and national programs represent systemic efforts toward the digitalization of education. The *PE Conectado* program is the Pernambuco Government's corporate telematic network, providing integrated telecommunication services to state agencies, including schools [SAD-PE, 2025]. *PE + Digital*, a program updated in 2024 with an investment of R$ 44 million, aims to develop the digital competencies of Education Secretariat staff by distributing notebooks to over 13,000 tenured teachers, analysts, and assistants [SEE-PE, 2025]. The *Escolas Conectadas* (Connected Schools) program, a federal joint initiative of the Ministries of Education and Communications, aims to universalize quality connectivity by 2026 with a national investment of R$ 8.8 billion, implemented in schools through the *PDDE Conectado* (*Programa Dinheiro Direto na Escola - Conectado*; Direct School Funding Program - Connected) [Brasil, 2025b].

These initiatives seek to operationalize the guidelines of the National Common Curricular Base (BNCC - from *Base Nacional Comum Curricular*, in Portuguese), which establishes the development of digital competencies as a cross-curricular responsibility in Brazilian basic education. General Competence 5 of BNCC prescribes that students must "comprehend, use, and create digital information and communication technologies in a critical, meaningful, reflective, and ethical manner" [Brasil, 2018, p. 9]. The 2022 BNCC Computing curriculum [Brasil, 2022], implemented as a complement to the original guidelines, further specify these digital competencies across all educational stages. However, tensions persist between uniform prescriptions and heterogeneous infrastructural realities [CETIC.BR, 2025; Vasconcelos *et al*., 2021], particularly with emerging disruptive technologies like Generative AI.

There is also limited knowledge on how different infrastructural configurations mediate technology appropriation processes by teachers, what adaptive strategies emerge in contexts of scarcity, and how teachers navigate emerging technologies while maintaining pedagogical autonomy. This gap is problematic because policies often assume contextual homogeneity, applying uniform solutions to heterogeneous realities [Cuban, 2001; Selwyn, 2021]. As Winner [1980] argues, technological artifacts embody political relationships, as their design materializes power structures and configures possibilities for action.

In this context, this study investigates, within the delimited setting of three urban schools from the Pernambuco state educational system with distinct institutional profiles (a Regular School, a State Technical School [ETE - from *Escola Técnica Estadual*, in Portuguese], and a Reference High School [EREM - from *Escola de Referência em Ensino Médio*, in Portuguese]), how teachers appropriate ICT in environments of heterogeneous infrastructure. Specifically, we explore four interrelated research questions (RQ):

- **RQ1:** How do different infrastructural configurations mediate the possibilities and limits of teacher technology appropriation?
- **RQ2:** What adaptive strategies do teachers develop to circumvent structural and teacher education limitations?
- **RQ3:** How do teachers navigate emerging technologies, especially generative AI, while maintaining pedagogical autonomy?
- **RQ4:** How do teachers pedagogically address topics of digital citizenship in contexts of systemic teacher education gaps?

With an exploratory nature, the investigation of these questions offers three provisional contributions to the literature:

1. We propose a heuristic typology of techno-pedagogical ecosystems that illustrates the analytical applicability of ecological perspectives [Zhao and Frank, 2003; Pischetola and Miranda, 2020] in specific contexts of Brazilian public education.
2. We document patterns of critical technology appropriation by teachers in constrained contexts, patterns that suggest reflective agency beyond the simplistic dichotomy between uncritical adoption and irrational resistance.
3. We analyze the emergence of AI in contexts of scarcity, examining tensions between optimization and precarization.

The convergence between the patterns identified here and established national diagnoses [CETIC.BR, 2025; CIEB, 2022; Vasconcelos *et al*., 2021] lends empirical plausibility to the analytical inferences presented. However, the proposed typology constitutes a provisional analytical tool whose applicability beyond the specific urban settings investigated here remains an open empirical question (see Section 5.6 for a detailed discussion of scope, limitations, and future directions).

The article is organized into six sections. Following this introduction, Section 2 presents the theoretical framework on infrastructure as pedagogical mediation and teacher appropriation in the use of ICT. Section 3 describes the methodological design, analytical procedures, and ethical considerations. Section 4 presents the results, organized in three groups of infrastructural conditions, followed by a cross-cutting comparative analysis. Section 5 discusses the findings in light of the literature, examines implications for public policies hierarchized by feasibility, and presents limitations and future directions. Section 6 synthesizes the investigation's theoretical and practical contributions.

2 Theoretical Framework

The ecological perspective recognizes that technological artifacts operate within complex systems where infrastructure, institutional culture, and teacher education mutually influence one another [Zhao and Frank, 2003; Pischetola and Miranda, 2020]. This systemic understanding is deepened by sociomaterial approaches, which demonstrate how the social and the material are constitutively intertwined [Orlikowski, 2007]. From this viewpoint, infrastructure is not a neutral backdrop against which pedagogical practices unfold, but rather a force that co-configures possibilities for action. Material configurations can, for example, reduce teacher agency through mechanisms of technical "lock-in" that limit viable pedagogical alternatives.

Recognizing these infrastructural mediations, it becomes crucial to understand how teachers appropriate technologies in specific contexts. Technology appropriation transcends linear models of adoption, constituting a complex process in which users adapt and resignify artifacts within situated practices [Carroll, 2004]. This perspective dialogues with two complementary concepts. First, the notion of "tactics" from Certeau [2014] enables an analysis of the operations through which subjects create agency within structural constraints, creatively transforming limited resources. Second, the capability approach of Sen [1999] highlights that conversion factors mediate the transformation of available resources into effective achievements, explaining why identical resources yield different outcomes in different contexts. Drawing on historical–cultural activity theory, Astudillo and Martín-García [2020] treat technology use as a mediated activity system, where participation links instruments, norms, and community, thereby transforming actors and contexts through situated appropriation processes that progress from initial adoption to creative integration.

These processes of technology appropriation, however, do not occur under equitable conditions. The literature on digital inequality has evolved from models focused exclusively on access to multidimensional approaches that encompass access, skilled use, and substantive outcomes, proposing dynamics of sequential accumulation of inequalities [Hargittai, 2002]. In the Brazilian context, this heterogeneity is particularly pronounced, with school infrastructure remaining drastically unequal across regions, school systems, and modalities [Vasconcelos *et al*., 2021; CETIC.BR, 2025]. As Pretto *et al*. [2013] demonstrate, nominal access to equipment does not guarantee effective pedagogical capacity, compromising equity when policies establish uniform expectations without considering contextual differentiations. This problem is not new: historically, technological educational reforms have failed precisely because they applied standardized solutions to heterogeneous realities [Cuban, 2001; Selwyn, 2021].

The emergence of AI adds layers of complexity to this landscape. Unlike previous technologies that relied on school infrastructure, consumer-facing generative AI applications (as distinct from API-based or institutionally integrated AI solutions, which require robust infrastructure) operate predominantly via personal devices, partially circumventing institutional infrastructure limitations. This differentiated accessibility, however, does not eliminate inequalities and may even amplify them. The integration of AI in education requires careful attention to ethical implications, methodological rigor, and systematic evaluation of impacts on teaching and learning [Bond *et al*., 2024], while challenging established assumptions about authorship, assessment, and mediation. In the Brazilian context, Pretto [2022] argues, from the standpoint of hacker ethics and critical pedagogy, that educational technologies should promote autonomy, collaboration, and horizontal cultural production, rather than reproducing logics of control and passive consumption. Moura [2024] complements this by warning that the accelerated adoption of AI without democratic participation and adequate teacher education poses risks to pedagogical quality.

This last point is critical. Teacher education for technologies is characterized by systematic fragmentation [Gatti *et al*., 2019; Cardoso *et al*., 2021]. Although teachers developed situated experiential knowledge during the pandemic [Oliveira and Pereira Junior, 2020], most have not received structured teacher education for the pedagogical integration of emerging technologies. In this context, perspectives that value teacher "bricolage" — creative adaptations in resource-limited contexts through tactical navigation [Certeau, 2014] — gain analytical relevance, recognizing that teachers develop agency even in the face of educational gaps and structural constraints.

Integrating these perspectives, this study defines "constrained contexts" as environments where infrastructural limitations, cumulative inequalities, and educational gaps restrict, but do not eliminate, possibilities for teacher action. Agency emerges from the situated interaction between teachers and their material and institutional environments [Priestley *et al*., 2015], a dynamic deeply influenced by the intersection of knowledge, self-efficacy, and pedagogical beliefs [Ertmer and Ottenbreit-Leftwich, 2010]. In this conception, infrastructure operates as an active mediation that shapes pedagogical possibilities without completely determining them. Teachers develop creative tactics to navigate systems they do not control [Certeau, 2014], while conversion factors (such as teacher education, institutional support, and school culture) mediate the transformation of available technological resources into effective pedagogical capabilities [Sen, 1999].

Figure 1 synthesizes these relationships. This theoretical framework enables the articulation of infrastructural determinants and teacher agency, allowing to examine how specific material contexts shape appropriation possibilities (RQ1) while teachers employ adaptive strategies within systemic constraints (RQ2). The framework presented here also provides theoretical grounds for understanding how teachers from three urban schools in Pernambuco produce practices

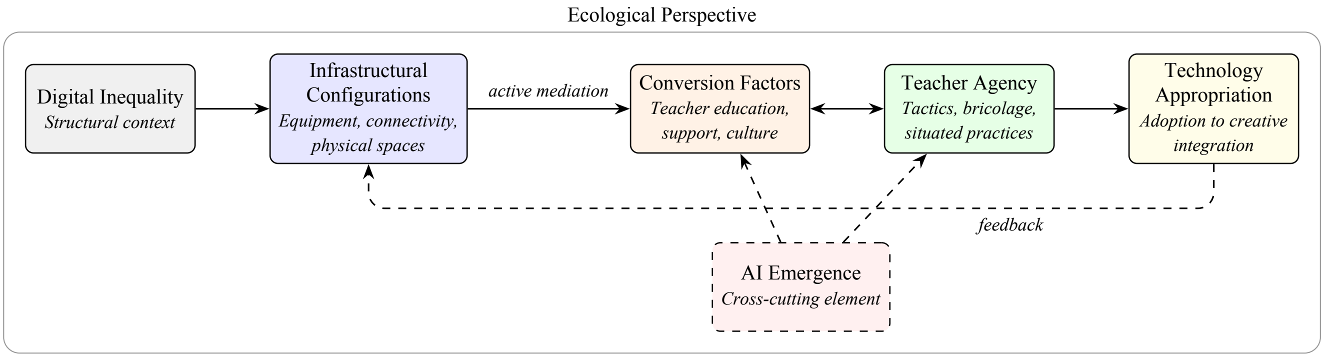

Figure 1. Theoretical framework: Infrastructure as active mediation of teacher technology appropriation. Digital inequality contextualizes how infrastructural configurations shape teacher agency through conversion factors, producing distinct appropriation patterns. Solid lines indicate associations identified in the empirical data; dashed lines indicate relationships theorized from the literature.

that incorporate emerging technologies with pedagogical autonomy (RQ3) and pedagogically address digital citizenship in contexts of systemic teacher education gaps (RQ4), without passively reproducing educational policies or depending exclusively on individual competencies.

3 Methodology

This study adopts a qualitative approach to investigate teacher technology appropriations in contexts of heterogeneous infrastructure, grounded in interpretivism, which recognizes the socially constructed nature of reality and the centrality of the meanings that actors attribute to their experiences [Denzin and Lincoln, 2018]. The choice of qualitative research is justified because the nature of the research questions, which investigate the "how" and "why" of teaching practices, demands a procedural analysis that quantitative methods cannot capture; the situated character of the phenomenon requires immersion in local contexts; methods that value the participants' voices are necessary; and the stage of theorization in the field calls for openness to the emergence of patterns [Yin, 2018; Merriam and Tisdell, 2016].

We adopted an exploratory comparative qualitative design [Merriam and Tisdell, 2016] to enable systematic comparison between contexts with distinct infrastructural configurations. This configuration prioritizes breadth of cross-site comparative insight over within-case depth, aligning with the study's objectives of generating a provisional typology and comparative hypotheses, and with the ecological perspective that posits the effects of educational technology are mediated by specific ecosystems [Pischetola and Miranda, 2020; Zhao and Frank, 2003].

3.1 Research Context and Site Characterization

The study was conducted in three urban state schools in Recife, Pernambuco, selected through purposive sampling [Patton, 2015]. The selection criteria aimed to encompass variations in both the type of institution (a Regular School, an EREM, and an ETE) and their infrastructural configurations, preliminarily identified through the researcher's prior knowledge of the schools. Geographical proximity was adopted as a bounding strategy to keep certain macro-level factors broadly comparable (e.g., shared jurisdiction under the same Regional Education Management unit, state-level policies, and urban socioeconomic context), while acknowledging that significant heterogeneity at the school and community levels, including institutional cultures, local management practices, and community characteristics, persists and may influence the observed patterns. This methodological delimitation aimed to reduce contextual variability, enabling the analysis to foreground the mediating role of infrastructure.

To deepen and systematize the knowledge of each school's infrastructural configurations, a formal characterization was conducted between August and September 2025, using a standardized structured questionnaire administered to the school heads of the three selected schools. The same instrument was sent digitally (via e-mail and messaging application) to all three school heads, who completed it independently. The questionnaire collected data on equipment (type, quantity, and distribution), connectivity (programs, scope, and reported functionality), laboratories (fixed and mobile), number of students and teachers, operating schedule, and school modality[1]. Additionally, the curricular matrix of each school was requested from the school heads, providing the basis for identifying disciplinary composition and the distinction between general education and technical components referenced in the site characterizations and participant descriptions below. All questionnaires were returned prior to the focus group sessions, enabling the on-site checks to function as targeted verifications of the reported conditions.

This information was then cross-checked against teacher reports during the focus groups and against direct on-site checks conducted at each school. Two visits were made to each school. During the first visit, conducted on the day of each focus group session, we verified the physical conditions of fixed and mobile laboratories (number of functional units, physical state, and spatial arrangement), tested network connectivity in instructional spaces (confirming the absence of functional Wi-Fi at School A, attempting connection to the school network at School B, and verifying classroom-level

[1] All supplementary materials are publicly available at: `https://bit.ly/3NSvYAl`. The repository includes: (a) school head questionnaire; (b) focus group script; (c) supplementation and field notes spreadsheet; (d) initial codebook (32 codes); (e) consolidated codebook (23 codes); (f) consolidation mapping; and (g) analytical matrix.

access at School C), confirmed operational details not fully captured by the standardized questionnaire (such as the distribution of teachers across shifts at School A, the only school operating in a multi-shift regime), and documented the general condition of available technological resources. A second visit, conducted during the follow-up verification described in Section 3.2.2, included confirmation of connectivity and teacher education data with the school heads. Observations were recorded as structured field notes organized by school, integrated into the same spreadsheet used for supplementation data (see footnote[1]).

These on-site checks were not systematic observation protocols with predetermined instruments; they constituted targeted verifications of specific material conditions reported by school heads and teachers, serving to corroborate or identify discrepancies in the independently collected data. This cross-source process revealed divergences between the formally available infrastructure and its effective accessibility, including cases where reports from school heads of nominal capacity diverged from teachers' experienced functionality (see School C below), a central element for the argument developed in this study.

Table 1 provides a comparative overview of the three schools' infrastructural configurations. The following descriptions detail each school's specific characteristics, institutional design, and the implications of their material conditions for the argument developed in this study.

School A, a Regular School, offers regular high school education (25 hours per week) in three shifts (morning, afternoon, and evening) and also Youth and Adult Education (EJA - from *Educação de Jovens e Adultos*, in Portuguese), although this latter modality was not included in the scope of this investigation due to its adult student profile and specific pedagogical features. The school has 46 computers distributed in 2 mobile labs (23 computers each) — which consist of transportable stations equipped with laptops, allowing them to be moved to different spaces in the school — serving 460 students distributed in the daytime shifts (237 in the morning, 223 in the afternoon), resulting in an aggregate student-to-computer ratio of 10:1, with variations by shift (morning: 5.15:1; afternoon: 4.85:1). It operates without a fixed lab and with connectivity inaccessible for pedagogical use (*PDDE Conectado* installed but not in effective use; no Wi-Fi in classrooms).

Although the afternoon shift has the most favorable ratio (4.85:1), it remains insufficient for activities requiring individual or small-group computer access, such as guided research, collaborative digital production, or the use of specialized software, since classes of 35 to 40 students would have access to only 7.2 computers per classroom if both mobile labs were used simultaneously. The aggregate 10:1 ratio masks these internal variations between shifts, but even the most favorable configuration makes such activities unfeasible in practice. The reliance on mobile labs without internet further compounds this constraint, imposing a logistical burden that disproportionately consumes pedagogical time (detailed in Section 4.1.1).

School B, an ETE, offers integrated technical high school education on a full-time basis (45 hours per week) and also subsequent professional education, although this latter modality was not included in the scope of this investigation due to its adult student profile and specific pedagogical features. The school has the largest physical endowment among the three schools investigated, with 161 computers distributed across 4 fixed labs (80 computers), 1 maker lab (20 computers), 2 mobile labs (46 computers), and computers in the library (15 computers), serving 480 students, resulting in a student-to-computer ratio of 3:1.

Connectivity constitutes a severe bottleneck, as *PE Conectado* is inaccessible in classrooms and unstable in the labs; *PDDE Conectado* is limited to the maker lab — the CRIA Space (*Criatividade, Inovação e Aprendizagem*, in Portuguese; Creativity, Innovation, and Learning), equipped with 3D printers, a laser cutter, robotics kits, and microcontrollers. The full-time schedule with 12 simultaneous classes intensifies competition for fixed labs, where 20 computers serve classes of up to 45 students, making individual work unfeasible. Technical curricula require intensive use of specialized software, making inadequate connectivity a critical constraint that creates a mismatch between physical endowment and curricular demands.

School C, an EREM [2], offers full-time high school education (45 hours per week). The school has an intermediate physical endowment with 141 computers distributed in 1 fixed lab (26 computers) and 4 mobile labs (115 computers), serving 303 students, resulting in a student-to-computer ratio of 2.1:1. It operates with connectivity classified as stable based on the convergence of the school head questionnaire, which reported *PE Conectado* effective in all classrooms with capacity for 600 simultaneous connections (*PDDE Conectado* for administrative use and the fixed lab), and our on-site verification, which confirmed functional classroom-level access. Teachers' reports during the focus group, however, included characterizations of connectivity as insufficient during peak usage periods, a divergence that illustrates the gap between nominal capacity and experienced functionality under real conditions of demand (9 simultaneous classes). The classification as "stable" reflects the comparative operational reality relative to the other investigated schools rather than an absence of constraints, and is supported by the independent on-site verification rather than by consensus across all sources. Despite a smaller physical endowment than School B, this connectivity profile is associated with greater operational functionality — a relationship examined in Section 5.1.

Connectivity was operationally classified based on the convergence of three independent sources: (a) the structured school head questionnaire, which identified the type, scope, and reported functionality of network programs at each school; (b) teacher reports during focus groups, which described the accessibility and reliability of connections in instructional

[2] EREM (Reference High School) is a strategic full-time education model implemented by the Pernambuco state government in 2008. Beyond extended hours, EREMs are characterized by a specific pedagogical framework focused on youth protagonism and "life projects", aiming to serve as a benchmark for educational quality through results-oriented management and enhanced infrastructure. Results-oriented management, however, is not exclusive to EREMs: it is a feature of the broader Pernambuco state educational system, applying to Regular Schools and ETEs as well. ETEs follow the same general education curriculum as EREMs, with the addition of integrated technical and vocational courses, constituting a more specialized institutional profile.

Table 1. Comparative Characterization of the Investigated Schools

School	School A	School B	School C
Modality	Regular School	ETE	EREM
Schedule	Part-time (3 shifts)	Full-time (45h/week)	Full-time (45h/week)
Teachers	12 (daytime)	31	20
Students	460 (daytime)	480	303
Computers	46 (2 mobile labs)	161 (4 fixed labs, 1 maker lab, 2 mobile labs, library)	141 (1 fixed lab, 4 mobile labs)
Student/PC ratio	Aggregate: 10:1 (Morning: 5.15:1; Afternoon: 4.85:1)	3:1	2.1:1
Connectivity	*PDDE Conectado* without pedagogical use; no Wi-Fi in classrooms	Unstable *PE Conectado*, no access in classrooms and unstable in labs; *PDDE Conectado* only in the maker lab	Stable *PE Conectado* in all classrooms; *PDDE Conectado* for administrative use and fixed lab
Projectors/TVs	1 projector	TVs in all classrooms; 2 projectors + 1 fixed in auditorium	4 projectors; 2 mobile TVs
Main constraint	Severe scarcity of equipment and connectivity	Inadequate connectivity for technical curricular demands	Competition for technology access in full-time schools

spaces; and (c) on-site checks conducted at each school, as described above. Based on this convergence, we classified connectivity as *inaccessible for pedagogical purposes* when the network existed formally but was not available in instructional spaces and teachers reported no functional access for classroom use (School A); as *available but unstable* when the network reached some instructional spaces but teachers reported frequent disconnections or functional unreliability that discouraged regular pedagogical use (School B); and as *stable* when teachers reported consistent access in classrooms without frequent interruptions, a characterization corroborated by the school head questionnaire and our on-site verification (School C), although teachers' reports also included perceptions of insufficiency during peak demand, as noted above. These classifications reflect reported and observed functionality rather than measured bandwidth or technical performance metrics. The comparative pattern summarized in Table 1, in which a larger physical endowment coexists with lower reported pedagogical functionality, constitutes the empirical basis for the functional inversion argument developed in Section 5.1.

3.2 Data Collection

Data were collected through three focus groups, one in each participating school, between August and September 2025. This period corresponds to the beginning of the second academic semester, capturing teacher perceptions after a complete first-semester cycle of work and the July recess. The choice of focus groups as the primary method [Barbour, 2018] was based on two reasons: (1) group interaction facilitates the emergence of data not accessible in individual interviews, fostering the collective construction of meanings; (2) the format proved to be pragmatically efficient given the teachers' heavy workload. The three sessions had different durations, with 42 minutes at School A (n=7), 50 minutes at School B (n=7), and 68 minutes at School C (n=11), reflecting both differences in group size and variations in the established interactional dynamics.

The moderation of the focus groups followed an approach that balanced a predefined script with the flexibility to delve into emerging themes. To ensure the richness and reliability of the data, specific strategies were employed, such as the equitable distribution of speaking turns, with direct invitations to less vocal participants; the focused redirection of discussions that strayed from the objectives; the encouragement of interaction among participants to deepen the collaborative construction of meanings; and the systematic recording of expressions of collective agreement and explicit dissent. Collective agreements were recorded when multiple participants explicitly expressed alignment (verbally or gesturally) with a colleague's initial statement. In the analysis, we interpreted these agreements as indicators of collaborative meaning-making when accompanied by elaborations or complementary examples, distinguishing them from passive acquiescences that did not lead to thematic deepening.

3.2.1 Rationale for the Focus Group Script

The focus group script was constructed based on the results of two prior quantitative investigations [Costa *et al.*, 2026]. The first analyzed data from the TIC Educação survey [CETIC.BR, 2025] to map national patterns of technology appropriation in the post-pandemic period. The second administered a questionnaire to teachers in the Pernambuco state educational system, investigating usage patterns, structural barriers, and perceptions of emerging technologies.

Although these investigations identified statistical patterns, they identified analytical gaps regarding the underlying processes that produced them. The first showed a predominance of instrumental use of ICT by teachers (46.3%), a disparity between administrative and pedagogical use, and critical infrastructural barriers (84.5% reported a lack of computers). The second identified gap was in in-service teacher education (49.84% did not participate), along with an emerging interest in technologies like AI. The script was informed by this evidence and structured around already validated dimensions: usage patterns differentiated by adoption levels; the impact of in-service teacher education on the complexity of practices; the role of infrastructural barriers and pedagogical support; and the appropriation of emerging technologies. This strategy preserved openness to themes emerging from group interaction and does not characterize a mixed-methods design in this study; instead, it involved using previous results to qualify the current qualitative exploration.

The semi-structured script was organized into six thematic blocks: (1) ICT Usage Patterns (6 questions on frequency, types of activities, and temporal evolution); (2) Teacher Education and Digital Competencies (6 questions on recent teacher education, current skills, and learning sources); (3) Barriers and Facilitators (5 questions on infrastructure obstacles and adaptive solutions); (4) Impact on Learning (2 questions on perceptions of change and their evidence); (5) Digital Citizenship (3 questions on security, disinformation, and privacy); and (6) Artificial Intelligence (3 questions on knowledge, use, and potential of AI in education). The full script can be consulted in the supplementary material[3].

3.2.2 Supplementation and Verification of Factual Data

During the preliminary analysis, the need arose to delve deeper into factual aspects and institutional dynamics that were not fully elucidated in the focus groups. This verification took place in September 2025, through individual contacts (via messaging apps and in-person meetings) with school heads and teachers from the three schools. Specific factual questions were prepared in advance, based on ambiguities and gaps identified during the preliminary coding of focus group transcripts. The questions focused exclusively on factual aspects, such as the origin, format, and scope of teacher education on technologies, especially AI; the distinction between the use of mobile labs in coordinated institutional activities versus individual pedagogical initiatives; and the dynamics of competition for technological resources among different disciplines.

The verification yielded three factual refinements that were integrated into the results. First, the characterization of School B's connectivity was confirmed, validating that *PE Conectado* remains inaccessible in classrooms and unstable connectivity in labs. Concurrently, *PDDE Conectado* is limited to the maker lab. Second, a critical distinction was identified in the contexts of mobile lab use: when used in coordinated institutional activities (external assessments, events), time constraints are absorbed by broad institutional reorganization; however, this support is unavailable for everyday individual pedagogical initiatives. Third, it was specified that in the last 12 months, the Secretariat of Education offered a single teacher education session on AI for assessments, with specific education (such as robotics) being selectively distributed without transparent criteria. The information obtained was systematically recorded in a structured spreadsheet organized by school (see footnote[1]) and used during Phase 4 (Mapping and Interpretation) to refine the contextual framing of patterns identified in the analytical matrix, without altering the interpretative patterns derived from the focus group data.

3.3 Participants

This study was approved by the Research Ethics Committee of the *Universidade Federal Rural de Pernambuco*, with Substantiated Opinion nº 7.458.736. Participants were recruited by direct invitation at the three selected schools, with the support of the school heads, to identify teachers who were interested and available to participate in focus groups. All participants signed an Informed Consent Form after receiving information about the study's objectives, procedures, potential risks, and their right to withdraw from the study. Participation was voluntary without financial incentives.

The groups consisted of a total of 25 teachers who voluntarily participated in three distinct focus groups: School A (n=7), School B (n=7), and School C (n=11). The participants represent significant disciplinary diversity, covering the general basic curriculum, technical components of professional education, and Specialized Educational Support (AEE - from *Atendimento Educacional Especializado*, in Portuguese). Teaching experience, ranging from 3 to 34 years, ensured the inclusion of multiple professional generations and teacher education trajectories. All were actively teaching during the data collection period.

The characterization of each group is detailed below:

- **School A:** a group of 7 teachers (4 female, 3 male), all working in the daytime shifts of the regular high school. Teaching experience ranged from 5 to 30 years, and academic qualifications included 2 with bachelor's degrees and 5 with specialization certificates. School A has a total teaching staff of 12 teachers across its daytime shifts. Participants covered diverse areas of the general basic curriculum, ensuring representation across the school's main disciplinary fields.
- **School B:** a group of 7 teachers (3 female, 4 male), with teaching experience from 3 to 34 years. Qualifications consisted of 1 participant with a bachelor's degree, 5 with specialization certificates, and 1 with a master's degree. School B has a total teaching staff of 31 teachers. Its composition, which integrated teachers of both general education and technical subjects, was strategic for analyzing the appropriation of technology on both fronts of the school's operation.
- **School C:** a group of 11 teachers (3 female, 8 male), with experience from 7 to 30 years. This group had the highest proportion of participants with formal qualifications, with 3 holding bachelor's degrees, 5 holding

[3]Available at: `https://bit.ly/3NSvYAl`.

specialization certificates, and 3 holding master's degrees. School C has a total teaching staff of 20 teachers. Participants covered both the general curriculum and specialized areas, reflecting the school's broad disciplinary scope.

Participants are identified throughout the text by alphanumeric codes (e.g., P1-A, P3-B) that indicate individual order and school affiliation. To protect anonymity, individual characterization details (specific disciplinary areas, exact years of experience, and postgraduate qualifications) are reported only in aggregate form per group, as the combination of attributes (teaching area, years of experience, school type) could enable identification within the local educational community.

The delimitation to three groups reflects pragmatic considerations of feasibility (access to schools, research timeline, teacher workload) and theoretical considerations (representation of the three proposed infrastructural types). The variation in group sizes (7, 7, and 11 participants) resulted from differences in teacher availability at each school rather than a deliberate design choice. School C's larger group reflects a higher number of teachers who expressed interest and were available during the scheduled session. In qualitative comparative research, the adequacy of group composition is assessed by the diversity of perspectives within each group rather than by numerical equivalence or proportional representation across sites. Each group ensured disciplinary diversity across the respective school's curricular areas, and the analytic procedures treated each school as a unit of comparison rather than aggregating individual responses, reducing the risk that group size asymmetry distorts cross-case patterns. The range of teaching experience within and across groups (3 to 34 years) was not controlled by design but was treated analytically as a source of variation, enabling the inclusion of multiple professional generations and diverse trajectories of technology appropriation. The study's purposive sampling is delimited to urban schools within a single metropolitan area; the implications of this delimitation for transferability are examined in Section 5.6. Within these boundaries, however, the sample is appropriate for the objectives of identifying qualitative patterns across heterogeneous urban contexts of the state educational system.

3.4 Data Analysis

The analysis followed the principles of *framework* analysis [Ritchie and Spencer, 1994; Gale *et al.*, 2013], a systematic method of qualitative analysis that allows for rigorous comparison between cases through a structured analytical matrix. Developed for applied public policy research, this method articulates deductive elements (categories derived from the script and theoretical framework) with inductive elements (themes emerging from group interactions), making it particularly suitable for comparative qualitative designs that seek to identify cross-cutting patterns and contextual variations. The analytical process consisted of five phases tailored to our context, which are detailed below.

Phase 1 - Familiarization and Data Immersion

All sessions were audio-recorded, with the explicit consent of the participants. All audio (160 minutes) was submitted in segments to Google Gemini 2.5 Pro for initial automated transcription, generating 44 pages of text. The principal researcher then conducted a full human review by re-listening to all audio recordings while reading the transcripts. Speaker labels generated automatically by the tool were verified against voice recognition and contextual cues (e.g., disciplinary references, continuity of argument), and corrections were applied where misattributions were identified. Technical terminology, regional expressions, and overlapping speech segments were also checked and corrected where necessary; overall, corrections were punctual rather than extensive, indicating adequate baseline accuracy from the automated tool. Segments that remained unclear after repeated listening were marked as inaudible rather than approximated. Paralinguistic elements (such as hesitations, self-corrections, and vocal emphases) were registered when semantically relevant to the analytical interpretation, rather than transcribed exhaustively.

Phase 2 - Identification of the Thematic Framework

The transcripts were coded, combining deductive perspectives (dimensions from the script: usage patterns, teacher education, barriers, digital citizenship, and AI) and inductive perspectives (emerging themes: techno-pedagogical bricolage, reflective resistance, generational inversion, and stratification by complementation). Manual coding in structured spreadsheets initially generated 32 codes (13 deductive + 19 inductive), organized into eight thematic dimensions: Usage Patterns, Infrastructural Ecosystems, Adaptive Strategies, Structural Barriers, Teacher Education, Critical Appropriation, Artificial Intelligence, and Digital Citizenship. Through iterative refinement during the transition to Phase 3, these were consolidated into 23 analytical codes (6 deductive, 1 mixed, and 16 inductive) within the same eight dimensions. The codebook, including code definitions, illustrative examples, and the consolidation trajectory, is available as supplementary material[4]. Although qualitative analysis prioritizes interpretative depth, we recorded the distribution of statements per participant and group to contextualize the representativeness of the identified patterns. Findings are presented by distinguishing between: majority patterns (corroborated by triangulation); significant, non-generalizable individual statements; and explicitly stated interpretive inferences.

The coding process was conducted by the principal researcher. To address potential single-coder limitations, two strategies were employed. First, *co-author review*: after the initial coding was completed, the co-authors reviewed the coded transcripts and the codebook. Divergences identified during this review, primarily concerning code boundaries and the classification of ambiguous passages, were resolved through systematic re-reading of the relevant transcript segments, with adjustments documented in the codebook. Second, *documented codebook evolution*: the transition from the initial 32-code framework to the consolidated 23-code version required revisiting all coded passages and justifying each consolidation decision, functioning as an additional consistency check. The consolidation mapping (including each removed code, its destination, and the analytical rationale) is documented in the supplementary material. While

[4] Available at: `https://bit.ly/3NSvYAl`.

this single-coder approach does not provide the independent replication that formal inter-coder procedures would afford, the combination of co-author review and a fully documented analytical trajectory ensures that the interpretive decisions are transparent and auditable.

Two examples illustrate the coding process. The code `PEDAGOGICAL_BRICOLAGE` emerged when two participants in School A independently described practices of recreating digital tools in analog formats, a pattern not anticipated in the deductive framework. This code was initially labeled `ANALOG_ADAPTATION`, then refined to `DIGITAL_TO_ANALOG_CONVERSION` as additional participant statements clarified the directionality and intentionality of the process, and ultimately subsumed under the broader analytical category of `PEDAGOGICAL_BRICOLAGE` during Phase 3. A second example illustrates a different analytical movement. The code `INFRASTRUCTURAL_ECOSYSTEM` was initially created inductively to capture the observation that each school's material configuration constituted a qualitatively distinct field of pedagogical possibilities, a pattern that transcended the individual barriers reported in response to specific script questions. During codebook refinement, this code absorbed two deductive codes (`OBSTACLES` and `INFRASTRUCTURE`, corresponding to Q13 and Q14) whose empirical content was already subsumed by the systemic characterization, leading to its reclassification from inductive to mixed.

Phase 3 - Construction of the Analytical Matrix

We organized the 23 consolidated codes into an analytical matrix (see footnote[1]) structured into the eight thematic dimensions identified in Phase 2. The process of creating the matrix involved summarizing relevant data while preserving the original context; identifying convergences, divergences, and deviant cases; and systematically organizing the data to visualize cross-cutting patterns and contextual variations. The theoretical interpretation of these variations, based on ecological perspectives and the capability approach of Sen [1999], enabled the construction of the typology of techno-pedagogical ecosystems.

Phase 4 - Mapping and Interpretation

The patterns organized in the matrix were interpreted in light of the theoretical frameworks, identifying (a) direct associations between infrastructure and practices; (b) complex mediations involving multiple factors; and (c) contradictions that revealed non-linear dynamics, such as the functional inversion between Schools B and C. Information from the supplementation of factual data (Section 3.2.2) was integrated in this phase, refining preliminary interpretations.

Phase 5 - Analytical Synthesis

The final phase produced an analytical narrative structured to answer the four research questions, reorganizing themes from the matrix in a logical manner. Direct quotations were selected for their representativeness, clarity, and illustrative power.

3.4.1 Quality and Rigor of the Analysis

The quality of the qualitative analysis was ensured by multiple strategies:

1. **Systematicity and audit trail:** All analytical steps, from initial coding through codebook refinement (32→23 codes) to matrix construction, were documented, maintaining traceability between raw data, thematic organization, and final interpretations. Statements that contradicted emerging interpretations were systematically identified and incorporated into the analysis, refining the understanding of dominant patterns. The strategies employed to address single-coder limitations (co-author review and documented codebook evolution) are described in Phase 2 above.
2. **Data triangulation:** We employed two distinct triangulation strategies, each serving a different function (cf. [Patton, 2015] on the multiple purposes of triangulation): (a) *triangulation for corroboration* — teacher reports from focus groups were compared with infrastructural data independently collected through a structured questionnaire administered to the school heads (Section 3.1). Additionally, on-site checks were conducted at each school (two visits per school, as described in Section 3.1) to verify reported material conditions, including cases where the verification resolved divergences between school heads' and teachers' reports. This cross-source comparison enabled the identification of discrepancies between formally available infrastructure and its effective accessibility, and provided independent verification of factual claims. The school head questionnaire is available as supplementary material (see footnote[1]); and (b) *triangulation for contextualization* — site-specific findings were situated within broader national patterns documented in large-scale surveys [CETIC.BR, 2025; CIEB, 2022; Vasconcelos *et al*., 2021]. This contextual alignment provides plausibility to the hypothesis that similar dynamics may operate in comparable settings, but does not independently validate the local interpretations.
3. **Supplementary data collection:** Follow-up contacts with school heads and teachers (Section 3.2.2) were conducted to refine factual aspects and clarify ambiguities identified during preliminary analysis. These contacts drew on the same institutional actors and thus do not constitute an independent source of triangulation; their function was to enhance the accuracy and completeness of the primary data rather than to provide external verification.
4. **Within-session thematic recurrence:** During each focus group session, we observed diminishing thematic novelty toward the latter portions of each discussion, with later contributions largely corroborating and elaborating upon themes introduced earlier in the conversation. However, we acknowledge that this within-session observation does not constitute thematic saturation in the stronger iterative sense, which would require additional cycles of data collection and analysis [Patton, 2015]. The findings should therefore be interpreted as provisional patterns that warrant corroboration through subsequent investigations with broader and more diverse samples.

The unequal distribution among schools (7, 7, and 11 participants) reflects pragmatic differences in teacher availability and does not compromise analytical comparability, as qualitative analysis prioritizes depth and variation of patterns over numerical equivalence.

4 Results

The results of this research are presented and organized into four analytical axes that correspond to the research questions: Infrastructural mediations and the configuration of techno-pedagogical ecosystems (RQ1); Adaptive teacher strategies (RQ2); Appropriation of emerging technologies (RQ3); and Digital citizenship in constrained contexts (RQ4).

Table 2 presents a comparative synthesis of the three identified techno-pedagogical ecosystems, organizing the findings according to the eight thematic dimensions of the analytical matrix constructed in Phase 3 (Section 3.4). Each cell synthesizes predominant patterns identified through multiple statements, without implying absolute homogeneity or the absence of individual variations documented throughout the analysis.

The subsequent analysis explores each dimension in depth, beginning with a detailed characterization of how different infrastructural configurations are associated with qualitatively distinct fields of pedagogical possibilities.

4.1 Infrastructural Mediations and the Configuration of Techno-pedagogical Ecosystems

In response to RQ1, our analysis gives rise to a provisional typology of three qualitatively distinct techno-pedagogical ecosystems associated with different infrastructural configurations. The Survival Ecosystem (School A) is characterized by the cognitive incorporation of technological impossibility into pedagogical planning; the Limited Adequacy Ecosystem (School B) features the largest equipment endowment but is functionally constrained by inadequate connectivity, generating a pronounced institutional duality in ICT use; and the Competition Ecosystem (School C) requires complex temporal orchestration of available resources. Across all three settings, the temporal cost of setting up technology was recurrently reported as a significant operational barrier. The following subsections detail the materialities of each ecosystem (Section 4.1.1) and their comparative operational logics (Section 4.1.2).

4.1.1 Materialities as Active Mediations of Pedagogical Possibilities

The data reveal that distinct infrastructural configurations are associated with qualitatively diverse fields of pedagogical possibilities. The convergence between our findings and multiple lines of empirical evidence (infrastructural data, teacher reports, and national patterns) indicates that infrastructure is associated with distinct operational logics.

School A - Survival Ecosystem

As characterized in Section 3.1, School A operates under severe scarcity of connectivity and basic technological resources. The structural absence of internet in the classrooms and poor mobile coverage create a fundamental barrier that makes the use of online resources unfeasible. One teacher explains "*that the connection, both Wi-Fi and 3G, has poor coverage here as well. The Wi-Fi doesn't reach the classrooms, which makes it impossible to use resources*" (P2-A). This condition highlights critical operational inadequacies that the teachers summarize: "*we run into structural issues... there's the will, but we still lack a real structure*" (P1-A). Infrastructural scarcity coexists with systematic deficits in students' basic digital competencies, compromising pedagogical use even on the rare occasions when resources are available.

To provide empirical grounding for each ecosystem's operational logic, we present below brief composite scenarios reconstructed from multiple teacher reports within each school. These vignettes combine elements from different participants' accounts to illustrate typical dynamics documented during the focus groups; they do not represent the literal experience of any single teacher. Direct quotations are attributed to specific participants.

The operational logic of this ecosystem becomes visible in everyday episodes reported by teachers. A Mathematics teacher who regularly uses gamification platforms such as Kahoot and Wordwall at another institution describes how, at this school, he has ceased to consider digital possibilities altogether: "*I no longer think about the virtual option; I always adapt. It's automatic*" (P2-A). A Portuguese teacher recounts attempting to use the school's single projector for a class activity, only to find that the bright, unshaded classroom rendered the projection nearly invisible. Moving students to another room consumed substantial class time, and the electrical installation proved unstable: "*if you touched something, everything went down*" (P5-A). With no Wi-Fi available in classrooms, poor mobile network coverage even in corridors, and no laptops available for teacher or student use, any activity requiring internet connectivity is effectively precluded. Teachers report that paper-based adaptations of digital activities, such as recreating the competitive structure of Kahoot using printed materials, have become a default strategy, one that achieves pedagogical objectives but forfeits the interactive engagement that motivated the original design: "*the pedagogical result you do reach, but it's not that excitement, the energy you expected from the activity*" (P2-A). One teacher exposes this difficulty: "*there's a difficulty because the kids don't have training, the skill to use them*" (P2-A).

This account documents a process in which structural limitations have been incorporated into routine pedagogical planning to the point of becoming, as the teacher describes, "*automatic*" (P2-A), a pre-conscious cognitive disposition where the digital option is excluded before deliberation begins. The analysis of the distribution of statements within the group reveals that the majority reported predominantly administrative use and low frequency due to structural limitations, converging with the pattern of cognitive adaptation explicitly articulated by this teacher.

Table 2. Comparative Synthesis of the Techno-pedagogical Ecosystems

Dimension	Survival (School A)	Limited Adequacy (School B)	Competition (School C)
Usage Patterns	Rare in classroom; administrative focus; frustrated attempts	Technical: daily (≈90%); General Ed.: variable (daily to almost never); institutional duality	Regular (≥3x/week); less variation; facilitated by infrastructure; exceptions by preference
Infrastructural Ecosystems	46 PCs/460 students (10:1); no Wi-Fi in classrooms; 1 projector; *PDDE Conectado* without pedagogical use	161 PCs/480 students (3:1); unstable *PE Conectado*; restricted *PDDE Conectado*	141 PCs/303 students (2.1:1); stable *PE Conectado*; *PDDE Conectado* for administrative use
Adaptive Strategies	Systematic techno-pedagogical bricolage (digital→analog conversion); normalization of impossibility	Direct appropriation without conversion; reorganization when labs are occupied; no creative bricolage	Ad-hoc situational adaptations; teacher tablets; purchase of ready-made materials (outsourcing)
Structural Barriers	Lack of basic access (equip./network); severe logistical issues (room changes)	Inadequate connectivity; temporal anticipation leads to giving up; undersized labs	Simultaneous coordination; network saturation; temporal constraint
Teacher Education	Abandonment of institutional teacher education; teacher education gaps; autonomous learning	Inadequacy of institutional teacher education; peer learning; autonomous learning	Inadequacy of institutional teacher education; peer learning; autonomous learning
Critical Appropriation	Not documented (impossibility of use limits reflective appropriation)	Intentional return to the board; reflective use; empirical comparison of modalities	Pedagogical subordination (technology as a means, not an end); balanced use reduces resistance
Artificial Intelligence	Instrumental use for materials; 2 cases of non-appropriation; optimism without critique	Diversified; pragmatic normalization coexists with critical vigilance; systematic validation	Integrated experimentation; 1 assistive case (Attention-Deficit/Hyperactivity Disorder - ADHD); ethical debates on AI; pragmatic ambivalence
Digital Citizenship	Episodic, reactive to incidents; no curricular articulation; ad-hoc approaches	"Digital Literacy" course; fragmented; disjointed individual initiatives	"Digital Culture" course; fragmented; administrative vs. pedagogical approaches

Note. The full analytical matrix is available at `https://bit.ly/3NSvYAl`.

School B - Limited Adequacy Ecosystem

As described in Section 3.1, School B has the largest physical endowment of resources; however, it is compromised by inadequate connectivity, which operates as a functional bottleneck. The fundamental problem lies in the network configuration. Although technical subjects demand specialized software and online resources intensively and mandatorily, the inadequate connectivity compromises the pedagogical use of ICT for most teachers, regardless of their discipline. The mobile labs exemplify resources that are physically available but functionally inaccessible — teachers in general education subjects report avoiding them entirely due to the absence of reliable connectivity, as detailed below.

The operational consequences of this mismatch become concrete in daily practice. Teachers in technical disciplines, whose curricula depend on specific software — such as design tools, physical simulations, or chemistry modeling — must reserve laboratory sessions in advance and compete for scheduling with other courses that equally require these spaces (P7-B). When a session is secured, the available computers serve classes that often exceed laboratory capacity: "*we have laboratories with 20 computers for classes of 45 students*" (P7-B), requiring paired work even when individual exploration would be pedagogically preferable. Connectivity compounds the problem: the *PE Conectado* network in laboratories is intermittent, disrupting activities that depend on continuous internet access. For general education teachers, these accumulated difficulties produce a distinct pattern of anticipatory avoidance. A Biology teacher explains his decision not to use the school's two mobile labs despite considering them a valuable resource: "*Why have I never used the mobile labs? Because I need the internet*" (P4-B). He adds that even when connectivity is set aside, the time required to organize a classroom for mobile lab use across two combined periods makes the effort impractical, leading him to abandon the attempt altogether (P4-B). A Chemistry teacher who has used simulation tools for teaching states of matter reports using technology in class "*almost never*" (P6-B), suggesting that the gap between available resources and functional conditions discourages even teachers with relevant technical skills.

This combination of inadequacies is associated with a radical institutional duality regarding the use of ICT. Teachers of technical subjects report intensive and mandatory use, in contrast to their colleagues in general education subjects, whose use varies from daily to sporadic. This variation does not indicate technological disengagement but a conscious modulation of use frequency, based on both different pedagogical demands and infrastructural constraints.

The variation in technology use occurs not only between technical and general education subjects but also within general education subjects. Even among teachers with similar curricular demands, the reported frequency of use varies widely, forming a spectrum from daily use to almost no use. This internal heterogeneity shows that technology appropriation is mediated not only by curricular demands but also by individual pedagogical choices, prior competencies, and perceptions of the educational value of the tools.

The curricular duality accentuates the competition for labs, pitting technical needs (perceived as a priority) against those of general education. In this scenario, teacher competence is redefined as the ability to manage pedagogical dilemmas that are, in essence, unsolvable without an infrastructural expansion that guarantees both equipment and stable connectivity.

School C - Competition Ecosystem

As characterized in Section 3.1, School C has the best student-to-computer ratio and superior connectivity, but the constraints are shifted to the temporal and organizational dimensions. Although designed for 600 simultaneous connections, the network is saturated in practice when multiple classes connect simultaneously. The school head partially attributes this congestion to students' insufficient digital literacy in accessing the network using their institutional credentials.

The mixed configuration of resources creates qualitatively distinct usage dynamics, requiring reservation systems. Although teachers positively evaluate the overall availability of resources, this proportional adequacy is often limited by organizational and temporal constraints that restrict pedagogical flexibility. This competition for access requires complex temporal orchestration, where the need for advanced coordination limits pedagogical spontaneity. Teachers report situations where the lab was occupied, forcing the cancellation of activities.

A typical challenge in this ecosystem involves temporal orchestration. A Geography teacher who uses gamification tools such as Kahoot and Wordwall regularly in class describes the mobile lab as a resource he frequently avoids because of time constraints: with single non-consecutive class periods, "*by the time I distributed everything, 30 to 40 minutes of class were gone, and it was over*" (P3-C). The alternative, the fixed computer lab, involves competition for access, as a Portuguese teacher notes: "*for the computer lab there is a dispute for access*" (P10-C), which discourages consistent planning around lab-based activities. When multiple classes simultaneously connect to the school's *PE Conectado* network, saturation becomes an additional barrier: "*the routers saturate very quickly when we have more than one class connected at the same time*" (P5-C). Teachers develop varied workarounds: a Physics teacher resolves connectivity-dependent activities by allowing students to use personal mobile devices (P11-C), while a Portuguese teacher who found the lab unavailable for a planned reading activity converted it into oral work and board-based exercises (P10-C). A Biology teacher recounts having to change the entire plan for an elective Cinema class, ultimately teaching a Biology topic instead, because no projector was available that day (P5-C).

4.1.2 Operational Logics of the Ecosystems

The comparative analysis of the three infrastructural configurations in the investigated contexts gives rise to the provisional heuristic typology presented in Table 2. As an analytical tool grounded in the patterns documented in these specific settings, the typology establishes associative relationships rather than definitive causal ones; the documented patterns constitute empirically observed correlations whose causal mechanisms require validation through longitudinal investigation, and other factors not controlled in this design (including pre-existing teacher profiles, institutional cultures, and local management policies) may mediate the associations reported here (see the end of this section for further discussion). Drawing on ecological perspectives [Zhao and Frank, 2003; Pischetola and Miranda, 2020], the typology characterizes three empirically distinct operational logics.

The **Survival Ecosystem** is characterized by the constant management of operational risk, in which each technological use represents an uncertain bet. The systematic anticipation of failures transforms material impossibility into a cognitive disposition, eliminating technological possibilities from the pedagogical planning horizon. The **Limited Adequacy Ecosystem** features abundant physical resources limited by inadequate connectivity, generating pronounced variation in use between technical and general education subjects. The **Competition Ecosystem** requires complex temporal orchestration of available resources, where the need for prior coordination limits pedagogical spontaneity, transforming access management into a central teaching competency.

These logics suggest that, in the contexts studied, the provision of resources is associated with qualitatively distinct types of constraints that demand different forms of teacher agency, not with a linear resolution of technology integration challenges. The observed relationship between infrastructural scarcity and the development of techno-pedagogical bricolage, in contrast to direct appropriation in School B, constitutes a documented associative pattern; however, other uncontrolled factors may mediate this relationship. The typology suggests that different infrastructural configurations are associated with qualitatively distinct constraints, rather than higher or lower levels of adequacy.

Specifically, the mediating factors noted at the outset of this section may shape the documented operational logics in ways this study cannot isolate. The contrast between Schools B and

C illustrates how such mediation operates alongside, rather than instead of, infrastructural conditions. School B holds the largest physical endowment of the three sites (161 computers, four fixed labs, a maker lab equipped with 3D printers and robotics kits, two mobile labs) and a curricular profile in which technical disciplines impose intensive and mandatory demand for specialized software. As argued throughout Sections 4.1.1 and 5.1, the primary factor that distinguishes its functional pattern from that of School C is inadequate connectivity rather than the institutional design of each school. Yet the comparison also reveals that infrastructural conditions are not the only dimension at work: School C autonomously organized additional in-service training on AI beyond the single session uniformly offered by the State Secretariat of Education (Section 4.2.2), a supplementation not documented at the other two sites, and its cross-disciplinary pattern of regular use contrasts with the sharp duality between technical and general education teachers observed in School B despite its larger physical endowment. These differences suggest that local management practices, the school's capacity to mobilize additional resources, and institutional cultures regarding technology use operate as secondary mediating factors that compound, but do not supersede, the infrastructural differential. Pre-existing teacher profiles, including prior technology experience, disciplinary background, and years of service, may also influence whether teachers develop bricolage strategies, direct appropriations, or anticipatory avoidance independently of the material conditions available. These factors interact with infrastructural configurations rather than operating in isolation, and the patterns documented here should be understood within this broader context of multiple, interacting mediating influences.

Among the operational constraints identified across all three ecosystems, the temporal constraint emerges as a particularly critical and often invisible barrier in technology integration analyses.

Temporal Constraint as a Critical Operational Barrier

The setup time for technological resources consumes a disproportionate part of the class. This phenomenon is particularly pronounced in the use of mobile labs, which necessitate transportation, distribution, and configuration for each use.

In School A, time is consumed by logistical unpredictabilities (room changes, electrical instability). In School B, the mere anticipation of the setup time leads teachers to give up on using them. In School C, a teacher quantified that distributing the mobile computers in a 50-minute class consumes between 30 and 40 minutes, leaving insufficient time for pedagogical work.

Subsequent verification with participants confirmed a critical distinction in the contexts of mobile lab use. When used in coordinated institutional activities (external assessments, events), these temporal constraints are absorbed by broad institutional reorganization: schedule adjustments, support from multiple staff members, and redistribution of responsibilities. However, this organizational support is not available for everyday individual pedagogical initiatives. The mobile labs operate adequately when there is broad institutional orchestration, but remain pedagogically inaccessible for everyday teacher technology appropriation.

4.2 Adaptive Teacher Strategies: Tactical Navigation in Constrained Structures

Regarding RQ2, teachers across the three schools develop differentiated adaptive strategies associated with their specific material contexts. In contexts of severe scarcity (School A), specific cases of techno-pedagogical bricolage (the creative conversion of digital activities into analog formats) were documented. In the Limited Adequacy setting (School B), teachers employ direct digital technology appropriations constrained by connectivity limitations. In the Competition Ecosystem (School C), adaptations are situational and reactive, responding to temporal coordination challenges. Across all settings, self-directed learning and informal peer networks appear to compensate for perceived inadequacies in institutional teacher education. The following subsections detail these strategies.

4.2.1 Techno-pedagogical Bricolage: an Adaptive Strategy in Contexts of Scarcity

Faced with scenarios of technological restriction, teachers develop sophisticated adaptive strategies that correspond to the tactics of Certeau [2014]. The analysis reveals, however, that the emergence of these tactics is not uniform.

Digital-to-Analog Conversion

In **School A**, two of the seven participants explicitly articulated practices of digital-to-analog conversion. The first describes in detail how he recreates gamification tools (Kahoot, Wordwall) in activities with paper, reporting that this adaptation from digital to analog has become an automatic response to structural scarcity (as discussed in Section 4.1.1). The second teacher reinforced the compulsory nature of this strategy, characterizing it as a professional imperative: "*I have to make this adaptation, [...] I have to present content, so I'll manage*" (P5-A). This account demonstrates an explicit awareness that bricolage is not a pedagogical choice but a necessary response to material impossibility.

These two documented cases exemplify an adaptive strategy that is theoretically consistent with contexts of severe scarcity. The characterization of these practices as a "necessary response" and "automatic" suggests that similar adaptive mechanisms, albeit implemented with different pedagogical techniques, may be operating among other teachers in this ecosystem. However, it is crucial to recognize that this is a theoretical interpretation based on two specific cases (2 of 7 participants): the empirical question of how widespread digital-to-analog conversion is as a strategy in School A and in similar contexts of severe scarcity in other schools and regions remains open for subsequent investigations with broader and more geographically diverse sample designs.

An important methodological observation is warranted here. The characterization of these practices as "digital-to-analog conversion" is grounded in the participants' own accounts: the teacher who most extensively described this practice explicitly referenced regular use of specific digital platforms (Kahoot, Wordwall) at another institution and described the adaptation to paper-based formats as a direct response to the infrastructural impossibility of using those tools at this school. This account was corroborated by a second participant who independently described adapting a digital game to a physical format. We acknowledge, however, that the focus group questions about strategies to circumvent infrastructural limitations may have encouraged participants to foreground the digital-to-analog framing over other possible characterizations of their practice, and that gamification with paper materials existed as a pedagogical strategy long before computational tools. Without classroom observation, the precise relationship between digital knowledge and analog practice cannot be independently verified, and the reported accounts remain consistent with at least three distinct interpretations: (i) a full digital-to-analog conversion, in which a previously digital activity is reconstructed in paper-based form once the digital pathway becomes infrastructurally unavailable; (ii) a refinement of pre-existing analog practices that the teacher has come to recognize and describe through a digital vocabulary acquired in other settings; or (iii) a parallel development of analog activities informed by digital awareness, in which knowledge of digital platforms shapes the design of paper-based activities without these activities being literal translations of any specific digital antecedent. Our analytical claim is therefore restricted to the direction of adaptation as reported by participants and to the documented incorporation of structural impossibility into pedagogical planning, not to a strong empirical demonstration of one of these three mechanisms over the others.

The analysis of this process reveals three critical dimensions. First, the adaptation ensures that central pedagogical objectives are achieved, as expressed by one teacher: "*the pedagogical result, you achieve it*" (P2-A). Second, the conversion compromises the motivational and affective dimensions inherent in interactive technologies, attenuating the engagement potential of digital activities. The same teacher acknowledges this loss: "*but it's not that excitement, the energy you expected from the activity*" (P2-A). Third, the process has become an automatic and pre-conscious response. The renunciation of technological possibilities occurs "before even a conscious consideration", which demonstrates the incorporation of structural limitations as a habitual disposition, in the terms of Bourdieu [1977].

We interpret these practices as demonstrating specific professional competencies, such as analyzing the structural elements of digital activities, identifying their essential components, and recreating their functional equivalents in an analog format. While participants described the practice itself (adapting specific digital tools to paper) and its experiential dimensions (achieving pedagogical objectives with diminished engagement), the formal characterization of this process as a structured sequence of decomposition and reconstruction represents our analytical interpretation rather than the participants' own articulation. This capacity for decomposition and reconstruction represents a critical technology appropriation that exemplifies the tactics of Certeau [2014], showing how teachers create agency within structural constraints by creatively transforming limited resources through practices mediated by situated contexts [Astudillo and Martín-García, 2020]. This techno-pedagogical bricolage, where technology is subordinated to educational values rather than institutional pressure, is not merely compensation for scarcity but an expression of sophisticated professional literacy that positions technology as a means to educational ends.

Direct Digital Technology Appropriations

With significant technological resources available (161 computers, 4 fixed labs, TVs in all classrooms), teachers in **School B** develop direct appropriations of digital technology, without the need for conversion to analog formats. When asked about creative solutions to circumvent infrastructural limitations, they did not report practices of digital-to-analog conversion. This absence reflects the availability of resources that enable technological use, albeit limited by inadequate connectivity.

Three interrelated dimensions characterize the ecosystem:

1. **Disciplinary variation based on curricular demands:** Technical teachers report daily and intensive use ("*90% of our classes*" - P7-B), while general education teachers show variable use. This differentiation responds to distinct curricular requirements: technical disciplines depend on specialized software on a daily basis; other subjects can alternate between technological and traditional resources according to pedagogical objectives.
2. **Technologically sophisticated appropriations:** These emerge in specific domains, including the use of Khan Academy with systematic analysis of individual learning data ("*the tool itself provides individual feedback for each student*" - P1-B); critical appropriation of AI, identifying "distorted concepts" and subjecting results to validation before pedagogical use; use of specialized simulators (PhET for Physics, GeoGebra for Mathematics, simulators of physical states for Chemistry); structured work with digital citizenship via the AVAMEC platform; and activities with augmented reality.
3. **Main operational constraint:** Competition for lab access is intensified by the full-time schedule with all classes present simultaneously. Fixed labs house 20 computers for classes of up to 45 students, limiting the individualized work advocated by the technical curriculum. Teachers report situations where necessary resources were occupied, requiring the reorganization of planned activities.

Situational Adaptations in the Competition Ecosystem

In **School C**, adaptations are situational and reactive, responding to temporal coordination rather than scarcity. When a planned resource becomes unavailable (e.g., an occupied projector), teachers improvise, substituting subjects or converting digital readings into oral discussions. While flexible, these adaptations lack the pedagogical sophistication observed in School A, as they involve substituting content or modalities rather than decomposing and reconstructing didactic structures.

The unequal distribution of adaptive tactics challenges assumptions connecting constraint to creativity. Severe scarcity (School A), as documented in specific cases (2 of 7 participants), coexists with the development of "sophisticated bricolage." The data suggest three potential mechanisms that could explain this association, although definitive causal relationships require longitudinal validation: (1) structural and predictable technological impossibility may allow for the development of systematized alternatives; (2) the absence of institutional expectations about technology use may free teachers to experiment with analog methods without professional stigma; (3) adaptation may become a central competency in the teaching repertoire, continuously cultivated and refined.

In contrast, limited adequacy (School B) is associated with what we tentatively characterize as an adaptive paralysis: a pattern of constrained adaptation that differs qualitatively from the bricolage documented in School A. As detailed in Section 4.1.1, partially available resources maintain the expectation of technological use, yet inadequate connectivity limits their pedagogical realization, producing the pattern of anticipatory avoidance documented above. The defining empirical feature of this pattern in School B is the group-level absence of articulated adaptive alternatives to digital technology. When directly asked about creative solutions to circumvent infrastructural difficulties (the same question that elicited rich accounts of digital-to-analog conversion in School A), none of the seven participants in School B reported a creative workaround, in marked contrast to both the bricolage accounts of School A and the situational adaptations documented in School C (Section 4.2.3). This absence is not reducible to disinterest or low digital engagement, since several teachers in this group (particularly in technical disciplines) report intensive daily use of technology when infrastructural conditions permit it. Three of the seven participants illustrate qualitatively distinct manifestations of this common absence. The Biology teacher (P4-B) reports never using the school's two mobile labs because of connectivity dependence ("*Why have I never used the mobile labs? Because I need the internet*"), gives up on mobile lab activities because of setup time, and describes a broader retrenchment in which post-pandemic tools such as Canva and YouTube "*stopped being used*" and he is "*going back to the board*" — a case of avoidance through retreat. The Chemistry teacher (P6-B) characterizes his use of technology in class as "*almost never*" and states that he "*always uses the board more*" despite holding relevant technical skills — a case of near-total non-use. The technical teacher (P7-B) reports using technology in "*almost 100%*" of his work, but identifies institutional structure as "*the main problem*" because "*we have disciplines that need to be taught in the lab and sometimes we do not have laboratories available*", without articulating any alternative pathway for delivering technical content when lab access or connectivity fail — a case of structural dependence without a fallback. Together, these three manifestations, combined with the group-level absence of creative solutions, sustain the interpretation of adaptive paralysis as a distinct ecosystem-level pattern rather than a feature of isolated cases. A fourth participant (P3-B, Mathematics) reports selective non-use, but attributes her decision to explicitly pedagogical rather than infrastructural reasons, noting that she tried using the projector to advance content and found the resulting dynamic unsatisfactory ("*I used it once [...] and it turned into a dull atmosphere in the room, I said, I don't want it anymore*"); this case lies outside the paralysis pattern and is noted here to delimit its scope. This configuration is associated with a distinct adaptive profile: across the group, teachers develop direct digital technology appropriations (as documented in the preceding subsection) but do not develop the systematic analog conversion strategies observed in School A. This pattern suggests that partial investments creating expectations without full fulfillment capacity may generate a specific type of constraint, distinct from total resource absence, that merits further investigation through longitudinal designs and broader samples. The theoretical implications of this adaptive paralysis are examined in Section 5.1.

4.2.2 Self-Directed Learning and Informal Learning Networks

The reliance on self-directed learning, observed in all groups, indicates a systematic inadequacy of institutional teacher education programs. Online tutorials, especially on YouTube, constitute the primary source of ICT learning for most participants. This reality highlights a structural mismatch between the situated needs of teachers and the standardized teacher education offerings. However, the reliance on informal platforms is not homogeneous, reflecting a hierarchy of learning sources that teacher education policies generally ignore.

The Hierarchy of Learning Sources

The learning sources reflect a pattern stratified by infrastructural context. In School A, one teacher articulates a precise sequence: first, colleagues at school (contextualized and immediate support); second, younger family members (domestic generational inversion); and, finally, online resources. The criterion is pragmatic: the search for someone who "understands" and "speeds up the process", valuing efficiency over in-depth learning. However, this hierarchy is not a cross-cutting pattern. In Schools B and C, most teachers turn directly to online tutorials (YouTube, TikTok) as their primary source, demonstrating greater autonomy and digital literacy. In School C, only one teacher mentioned colleagues as a primary source of support. This divergence suggests that contexts of extreme precarity generate dependence on face-to-face human mediation to compensate for access or digital literacy barriers. In contrast, contexts with better infrastructure enable autonomous learning via digital platforms. This dynamic is articulated with communities of practice [Lave and Wenger, 1991], but it suggests that, in these contexts, these communities form informally to compensate for institutional gaps, rather than being cultivated by coordinated policies.

Collaborative Peer Learning

In School C, an informal peer-learning initiative emerges as an alternative to the lack of formal teacher education. A teacher recorded YouTube tutorials to teach colleagues how to use the Moodle platform. This practice, which replicates the self-directed learning model, demonstrates an emerging community of practice that compensates for institutional failures. Most teachers in all three groups confirm the existence of these support networks, but their informality compromises their sustainability and reach.

Stratified Teacher Education Demands

The demands expressed by teachers regarding desired teacher education reproduce the infrastructural stratification, illustrating how different material contexts shape differentiated horizons of professional development. In School A, teachers articulate elementary needs — "*learning to work the computer better*" (P6-A), "*basic teacher education to feel more confident*" (P5-A) — revealing deficits in fundamental digital literacies that should have been developed in pre-service or in-service teacher education. In School B, demands are centered on AI applied to education (P5-B) and Google Classroom (P4-B), indicating a consolidated technical base focused on optimizing existing professional practices. These demands, while pedagogically oriented, concentrate on specific tools for current workflows rather than the expansion into new technical domains observed in School C. In School C, they present sophisticated demands, such as gamification, Python programming, and application development. Notably, these demands emerge among teachers who already incorporate similar tools in their pedagogical practice (e.g., gamification platforms, app development in elective courses), suggesting that accumulated experience with functional technology use may expand professional development horizons, a pattern further contextualized by the supplementary training dynamics documented in the following subsection.

The only cross-cutting convergence among the three groups relates to the need for teacher education in AI, though it manifests at qualitatively different levels: basic instrumental use in School A, pedagogical application in School B, and advanced customization in School C. This stratification in educational expectations does not appear to be contingent but structural, suggesting that contexts of scarcity may limit imagining sophisticated uses, while adequate infrastructure expands professional repertoires and ambitions.

Inadequacy of Institutional Teacher Education

Institutional teacher education programs present a complex pattern marked by structural inequalities. Over the last 12 months, the State Secretariat of Education has offered a single teacher education session on the use of AI for assessments, which has been applied uniformly to all schools in the system. However, inequality manifests in two distinct dimensions. First, through the selective distribution of specific teacher education, such as the robotics course offered exclusively to School C, without transparent selection criteria. Second, through unequal supplementation by local initiatives. School C, for example, autonomously organized an additional, more comprehensive, and specialized teacher education on AI, which the teachers positively evaluated. This setup characterizes a new type of inequality, where schools with greater social and organizational capital supplement basic institutional offerings, while others remain dependent on the minimum provided centrally. It is noteworthy that even schools with adequate infrastructure, like the ETE (School B), which has a maker lab, do not necessarily receive corresponding teacher education, highlighting a mismatch between material investment and the development of teacher capacities.

In School A, the teacher education offered is severely criticized for its lack of context. Teachers describe it as overly theoretical and distant "*from practice, from reality*" (P2-A). The criticism is so intense that it leads to abandonment, with teachers reporting they stopped attending because they "*lost the pleasure of being there*" (P2-A). While teacher education is criticized in School A, success in applying knowledge about AI is reported in School C. This variation suggests that the perceived quality of teacher education and the ability to apply it depend on infrastructural conditions.

4.2.3 Generational Pedagogical Inversion

In addition to techno-pedagogical adaptation strategies and self-directed learning, the data document a systematic phenomenon of pedagogical inversion in which students teach specific technical skills to teachers. Unlike bricolage, which adapts available resources, and self-directed learning, which seeks external sources of knowledge, pedagogical inversion represents a reconfiguration of teaching and learning relationships within the school context itself. This inversion indicates superior student technical literacies in specific domains, manifesting in spontaneous and unplanned situations that temporarily subvert traditional knowledge hierarchies.

Pedagogical Inversion in Schools B and C

In School C, one teacher learned to edit videos with students, while another was assisted in finding a public domain film to download. These cases (2 of 11 participants) indicate that pedagogical inversion occurs spontaneously when adequate infrastructure enables activities that demand specific technical literacies. However, it does not constitute a generalized pattern within the group.

In School B, the inversion manifests with greater frequency and systematicity. One teacher reports that while teaching the creation of geometric solids in GeoGebra, students autonomously explored the software beyond the taught content, discovering 3D rotation features and sharing knowledge with their peers. Another teacher describes a recurring practice. When he proposes technological activities, students often suggest alternative approaches, to which he responds: "*So teach me*" (P4-B), delegating instructional leadership to them in the lab. Additionally, teachers mention learning about social media from students. These cases (3 of 7 participants) suggest three dynamics. First, students develop exploratory literacies when technologies are pedagogically mobilized; second, peer learning (student-to-student and student-to-teacher) occurs spontaneously in technologically active environments; third, teachers demonstrate pedagogical reciprocity, institutionalizing student expertise without professional embarrassment.

Absence of School-based Inversion in School A

However, this pattern is not universal. In School A, teachers deny learning from students in the school environment. Critically, generational inversion occurs within the family ("*at home, the youth [...] guide me*" - P5-A), but not at school. This absence is significant and suggests either that students from precarious contexts have less developed digital literacies, questioning the notion of universal "digital natives" [Prensky, 2012],or that the limited use of technology in the classroom does not create opportunities for students' existing skills to manifest.

Distinction Between Family and School-based Inversion

The convergence between family and school-based inversion points to a systemic teacher education gap, which is compensated for by informal intergenerational networks. There is, however, a fundamental difference. Family inversion is intentional and requested (teachers seek help from their children or nephews/nieces at home), whereas school-based inversion arises spontaneously from pedagogical activities (situations where student literacies become evident during tasks). This dual inversion highlights the inadequacy of teacher education policies that fail to develop basic digital literacies in teachers, transferring the responsibility for this gap to informal networks.

4.2.4 Selective Technology Appropriation as a Professional Competency

Teacher technology appropriation is characterized neither by uncritical adoption nor irrational resistance, but by a pedagogically grounded selectivity. Teachers develop their evaluation criteria, deciding when, how, and whether to use ICT.

In School B, three teachers articulated deliberate choices not to use technology in specific contexts, based on observed pedagogical criteria. One teacher reported a longitudinal observation that students "*lost reasoning skills because they stopped writing*" (P4-B), justifying an intentional return to using the board. His analysis distinguishes between complementary use (acceptable) and substitutive use (problematic) of technology, recognizing that "*the notebooks are all blank*" (P4-B) when teacher mediation does not set limits. This reflection is based on a concrete pedagogical criterion (development of reasoning through writing), not on an ideological resistance to technology per se. Another teacher reported following the literature on the subject, mentioning that educational systems "*are backtracking*" (P6-B) on intensive use due to a lack of proper evaluation, demonstrating informed participation in contemporary academic debates. A third teacher reported that projection generated "*lethargy*" (P3-B), while classes at the board kept students "*agitated*" (P3-B), citing student preferences ("*they prefer it more on the board*" - P3-B) as empirical evidence.

These individual statements, while not constituting a group consensus (another teacher stated he "*hardly ever used the board*" - P2-B), demonstrate an analytical sophistication that subordinates technology to pedagogical values. The conscious choice for traditional methods in specific contexts represents a critical appropriation of technology, not irrational resistance. This competency of selective appropriation also manifests in relation to institutional teacher education: teachers are not passive recipients but develop the ability to extract and adapt useful elements even from inadequate teacher education, exemplifying the creation of "third spaces" [Zeichner, 2010] where academic and practical knowledge are hybridized through critical negotiation.

Additionally, the investigation identified two emerging phenomena, although tangential, that signal relevant contemporary dynamics. First, the commercialization of ready-made digital pedagogical materials, observed in School C, where one participant reported purchasing "*ready-made slides with BNCC skills*" (P7-C), suggesting the emergence of a market for standardized pedagogical resources. Second, the growing use of personal devices (tablets) for pedagogical management functions, reported in Schools B and C, indicating that teachers compensate for institutional inadequacies with their own resources.

4.3 Appropriation of Emerging Technologies: AI as a Disruptive Force

In response to RQ3, the appropriation of AI manifests in qualitatively distinct discursive and operational patterns across the three settings. School A exhibits cautious, instrumentally limited appropriation focused on material preparation — including cases of non-appropriation — accompanied by a discourse of technological optimism with limited explicit engagement with risks. School B shows functionally diversified appropriation with explicit critical vigilance. School C demonstrates more pedagogically integrated experimentation. Across all groups, the use of AI by students is reported as prompting adaptations in assessment practices. These patterns are described below.

4.3.1 Differentiated Patterns of Technology Appropriation and Compulsory Reconfiguration

School A: Cautious and Instrumentally Limited Appropriation

In School A, a context of marked scarcity, the appropriation of AI is cautious and instrumental, restricted to the preparation of teaching materials on personal devices with a home connection. Teachers who use AI (5 of the 7 participants) report using it to develop pedagogical resources, plan lessons, and create assessments. Direct pedagogical use with students was not mentioned. This gap between administrative preparation and classroom application suggests that the absence of school connectivity and infrastructure, coupled with the restrictions imposed by Law No. 15,100/2025 Brasil [2025a] limiting the use of personal mobile devices in schools, creates a dual barrier to AI integration. In scenarios where the school does not provide equipment, the student's device is the only alternative for access; however, the regulatory framework ultimately discourages personal use strategies, rendering student experimentation unfeasible.

Notably, two teachers were utterly unaware of AI tools, representing a non-appropriation that delimits the scope of the observed patterns. Significantly, these teachers did not participate in the AI teacher education offered by the State Secretariat of Education in the last 12 months. This example demonstrates that digital exclusion persists at elementary levels of knowledge, challenging narratives about universal access to emerging technologies. The lack of knowledge about AI, despite its accessibility via personal devices and widespread publicity, suggests that barriers extend beyond mere technical availability, encompassing factors such as digital literacy, learning networks, and, crucially, structural conditions of access to in-service teacher education.

Among the user-teachers, the discourse emphasizes potentialities without explicit mention of risks ("*it has potential*" - P2-A, "*the future of education is artificial intelligence*" - P1-A). This discursive pattern contrasts with those observed in Schools B and C, where teachers articulated both benefits and risks.

School B: Functionally Diversified Appropriation with Critical Vigilance

In School B, the appropriation of AI is functionally diversified, encompassing the production of slides, creation of activities, and development of educational games, demonstrating integration into the regular workflow and pointing towards technological normalization. Specific applications include creating questions for different levels, adapting teaching materials, and developing activities aligned with curricular demands.

In parallel, a critical appropriation emerges, characterized by the identification of the technology's conceptual limitations. One teacher characterized AI as "problematic" (P6-B), as concepts often "*come out completely distorted*" (P6-B). Three teachers explicitly used risk-benefit metaphors: "*dangerous, but it helps a lot*" (P2-B); "*great, but at the same time dangerous*" (P4-B); characterizing a critical vigilance verbalized during systematic use. This dual stance does not represent fragmentation but reveals an analytical sophistication, as teachers who integrate AI into their regular work do so without developing uncritical trust. This configuration of simultaneous critical vigilance and functional experimentation, which we characterize as *pragmatic ambivalence*, is further elaborated in Section 5.4.1. Instead, they subject the results to systematic validation based on their empirical experience of the errors inherent in AI. The pattern shows that these teachers are neither passive adopters nor irrational resisters, but reflective users who develop their own criteria for quality and reliability.

School C: Pedagogically Integrated Experimentation with Pragmatic Ambivalence

In School C, the appropriation of AI evolves into more pedagogically integrated and advanced experimentation. Teachers report developing activities that explore the capabilities and limitations of different tools, integrating discussions about ethics and AI into regular pedagogical work. The relatively superior infrastructure allows for greater direct experimentation with students.

At least two teachers articulated explicit ambivalence: one used the metaphor of a "*double-edged sword*" (P5-C), emphasizing both help and risk simultaneously, while another expressed distrust ("*I don't fully trust it*" - P10-C) coexisting with pragmatic use for work optimization. This ambivalent use does not imply paralysis: teachers report systematic functional use accompanied by explicit and verbalized critical vigilance during use.

A sophisticated use that transcends strictly school-related applications was also identified: one teacher customized an AI for non-educational purposes (an investment portfolio), demonstrating advanced and self-developed technical literacy. Additionally, a teacher explained that the tool has been helping him with "*organizational issues*" related to his ADHD diagnosis, revealing a use that aims to compensate for challenges associated with neurodiversity, a dimension often neglected in discussions about AI in education. A correlation was also observed between AI use and workload constraints. Teachers with reduced teaching loads in certain subjects (one class per week per group) report using AI to expedite the process of creating pedagogical materials, enabling efficiency in planning and preparing lessons. This relationship illustrates how technology is leveraged to address the structural issues of teaching work intensification, representing not a purely pedagogical choice, but a pragmatic response to labor conditions that demand a level of productivity difficult to achieve through traditional means.

Compulsory Reconfiguration of Assessment Practices

Across all three groups, teachers identify a growing use of AI by students to complete assignments, manifested in standardized responses that are easily recognizable as artificial. An "arms race" dynamic develops, in which the evolution of tools constantly outpaces teachers' detection capabilities. Although they report having developed a "radar" to identify AI-generated texts, teachers acknowledge the growing limitations of this strategy in the face of technological sophistication, which is associated with professional anxiety about the obsolescence of their assessment competencies.

This forced obsolescence highlights specific professional tensions: the need to redesign activities without adequate teacher education, pressure to develop technical competencies that extend beyond their area of expertise, and ethical dilemmas about tools that are not yet fully understood pedagogically. In School C, one teacher observed that students are using AI "*as an end, not as a means*" (P5-C). This distinction represents an attempt to establish pedagogical criteria for acceptable use. However, such normativity appears reactively, rather than through proactive institutional policies, transferring the responsibility of developing ethical frameworks to individual teachers, who should elaborate them collectively.

4.4 Digital Citizenship: Teacher Education Gaps and Individual Responsibility

Regarding RQ4, digital citizenship education is characterized by pervasive fragmentation across all three settings. A cross-cutting consensus on students' inability to critically evaluate online information contrasts with the absence of structured, curricular approaches to develop these competencies. The degree of formalization ranges from episodic interventions (School A) to a dedicated but insufficiently cross-curricular discipline (School C). When problematic situations arise, responses tend toward reactive and administrative approaches, particularly in School C, rather than sustained pedagogical strategies.

4.4.1 Consensus on Students' Lack of Critical Ability

In all three focus groups, the perception of students' inability to critically evaluate online information emerged as a recurrent and cross-cutting theme. When asked about students' skills in assessing reliability, teachers from all schools (A, B, and C) expressed a convergent negative view. In School C, this perception was collaboratively elaborated: after an initial statement by one teacher, multiple colleagues supplemented it with specific examples of observed situations, collectively constructing the characterization of student difficulty. In Schools A and B, teachers expressed similar assessments but with less collective elaboration. No teacher in any group expressed explicit disagreement or presented contrary evidence to this perception.

In School C, teachers stated that students "*don't correlate*" (P3-C) information and "*absorb*" social media content "*without actually observing if it's true or not*" (P7-C). This stance suggests the absence of evaluative filters that should mediate the reception of information in the digital environment. One teacher described a pedagogical activity that exposed this inability. When asked to research reliable news sites, students consistently showed a dependence on teacher validation, repeatedly questioning whether the sources were safe. The difficulty of performing the task autonomously persisted even after the teacher "*tried to explain*" (P6-C) the evaluation criteria, revealing "*a lot of dependence*" (P6-C) in forming their own judgments.

This situation reveals three dimensions of the problem. First, students do not have autonomous criteria to assess the reliability of sources; second, the dependence on external validation highlights a lack of prior development of these literacies; third, the teacher's difficulty in "*explaining it somehow*" suggests that transmitting such criteria is not trivial, requiring specific and structured curricular work. Additionally, one teacher identified a behavior that might explain this difficulty: the search for "*the answer for now*" (P7-C), in which adolescents "*take the answer [...], but often don't even bother to read if the answer is consistent with the question*" (P7-C). This instrumental orientation, which prioritizes efficiency over comprehension, may be reinforced by digital environments that value speed over reflection.

This perception transcends the infrastructural differences between the schools. It challenges assumptions about universal digital competencies, highlighting a critical gap in the implementation of skills outlined by the BNCC Computing [Brasil, 2022]. The document includes specific skills related to criticality and the veracity of information, such as evaluating the accuracy, relevance, and biases in electronic sources (EF08CO11), evaluating the veracity and credibility of information by identifying its purpose (EF09CO10), and investigating the reliability of digital information considering the authorship, structure, and purpose of the message (EM13CO14). Such convergence of opinions suggests a systemic educational challenge that cannot be solved merely by providing technology, but requires the development of these specific critical literacies provided for in the curriculum.

The documented critical inability demands articulation with theoretical perspectives on critical digital literacy. Livingstone and Third [2017] argue that effective digital competencies require not only technical skills but also the development of resilience and critical thinking that empower children and young people to navigate the risks and opportunities of the digital environment autonomously. The dependence on teacher validation observed in pedagogical activities directly contradicts this perspective of critical autonomy, suggesting that students remain at an elementary stage of digital literacy, one that privileges access and technical operation, without reaching the evaluative and reflective dimensions necessary for full digital citizenship.

The causes of this widespread critical inability cannot be reduced to individual student deficiencies. The documented instrumental orientation ("*the answer for now*") suggests that logics of productivity and efficiency, amplified by digital platforms that reward rapid engagement, may be colonizing cognitive processes that should be deliberative. Additionally, the absence of systematic curricular work on source evaluation (documented in the fragmentation discussed below) indicates that students do not receive structured opportunities to develop such competencies. Finally, contemporary digital culture itself, characterized by accelerated information flows and algorithms that personalize content exposure, may be undermining the cognitive and temporal conditions necessary for critical evaluation. These structural causes necessitate pedagogical interventions that are not limited to "explaining" criteria, but rather build learning environments that slow down information reception and systematically exercise critical judgment.

4.4.2 Fragmentation of Digital Citizenship Education and the Externalization of Responsibilities

The work on digital citizenship is characterized by systematic fragmentation and dependence on individual initiatives, which vary significantly in quality and scope according to the competencies and motivations of isolated teachers. This fragmentation starkly contrasts with the integrated and cross-curricular approach recommended by specialized literature and prescribed by the BNCC Computing [Brasil, 2022].

School A: Episodic and Reactive Approach

In this school, the approach is characterized by episodic individual initiatives without systematic curricular articulation. Two teachers reported working on digital citizenship: one stated doing so "*whenever possible*" (P5-A), focusing on fake news and the dissemination of information; another described a reactive intervention upon identifying problematic use of AI, stopping the class to explain the risks. The characterization as "episodic" is based on the expression "*whenever possible*" (curricular opportunism versus systematic planning) and the absence of a dedicated curricular component or institutional project.

School B: Disjointed Individual Initiatives

In School B, significant individual initiatives are observed, yet they are disconnected from an integrated curricular project. Paradoxically, although the technical school offers a "Digital Literacy" course (taught by a teacher not participating in this investigation), the work on digital citizenship remains fragmented among other curricular components, showing a lack of transversality. One teacher uses the media education module of the AVAMEC platform with his students. Although structured, this action contrasts with the absence of systematic work in other subjects. Another teacher, upon noticing that students use AI as an end rather than a means, planned a specific lesson on the topic, a responsive but isolated initiative. A third stated that he addresses safe and ethical use "*always*", but admits that he "*doesn't work on the topic directly, only in observations*" (P7-B), giving the theme a peripheral character rather than a central pedagogical objective.

School C: Structuring Focused on Specific Disciplines

In School C, the curricular structure exhibits the highest degree of formalization among the three investigated contexts, with the implementation of the "Digital Culture" discipline in 2025, replacing the previous "Innovation Track". One teacher systematically teaches the content, following the pillars of digital citizenship and representing the institutionalization of the theme. However, the existence of a dedicated discipline does not eliminate fragmentation. In the previous year, another teacher had already addressed topics like fake news and cyberbullying in the old track, while a third developed interdisciplinary awareness projects on their own initiative, without articulation with the formal curricular component.

Implications of Fragmentation and Infrastructural Inequality

The systematic comparison between the three groups suggests a progressive pattern of institutionalization: School A shows only episodic and reactive interventions; School B has a specific discipline but without effective transversality; School C has implemented a more recent formal curricular component. However, in all contexts, fragmentation persists as a structural feature. This progression correlates with the availability of institutional capital and infrastructural resources: schools with greater adequacy can formalize curricular components. At the same time, contexts of scarcity remain dependent on voluntary and precarious teacher initiatives.

This correlation links the fragmentation of digital citizenship education with broader infrastructural inequality. Students in contexts of greater deprivation not only face limitations in technical access but are also structurally excluded from formal opportunities to develop the critical competencies necessary for safe and ethical digital navigation. Consequently, material inequalities are amplified into inequalities of critical literacy, creating a vicious cycle in which those who most need protective and emancipatory competencies are precisely those who receive the least structured teacher education.

The identified fragmentation contrasts with the assumptions of the BNCC Computing [Brasil, 2022] regarding systematic curricular progression. Why do isolated disciplinary approaches fail? First, digital citizenship requires contextual application across multiple disciplines, such as evaluating historical sources in History, analyzing graphs in Mathematics, and interpreting news in Portuguese Language, and cannot be developed abstractly in a single component. Second, concentrating it in a specific discipline externalizes a collective responsibility, allowing other teachers to consider the topic "already covered" without integrating it into their practices. Third, the lack of transversality prevents students from perceiving digital citizenship as a competency applicable to all areas of knowledge and life, thereby reducing it to a disciplinary content that is disconnected from everyday digital experiences. Finally, the dependence on individual motivation, devoid of systematic institutional support, adequate materials, or in-service teacher education, results in heterogeneous practices that reproduce inequalities: only students whose classes are assigned to engaged teachers receive any education in digital citizenship, while others remain on the sidelines of developing these critical competencies.

4.4.3 Reactive versus Preventive Approaches

Problematic situations, such as cyberbullying, are systematically handled reactively through administrative referrals. In School C, teachers report that cases of student defamation on social media were resolved by the school head, with the explicit caveat that interventions are of an administrative and disciplinary nature, not a pedagogical and educational one. In Schools A and B, the absence of reports of intervention may indicate that such problems do not come to the teachers' attention, are referred directly to the school head, or remain invisible. The documented interventions are limited to addressing immediate problems but do not develop preventive competencies or a critical understanding of the digital dynamics that give rise to these conflicts, thereby wasting pedagogical opportunities to transform conflicts into learning experiences about digital citizenship.

5 Discussion

The findings of this investigation indicate that teacher technology appropriation is a phenomenon substantially more complex than simplifying dichotomies suggest. This section examines five analytical dimensions emerging from the data. The analysis questions established assumptions about technology integration in education and explores the theoretical and practical implications of the identified patterns.

5.1 Infrastructure as Active Mediation: Articulating Ecological Perspectives

The typology of techno-pedagogical ecosystems documented in Section 4.1 provides empirical grounding, within the investigated contexts, for the theoretical understanding of infrastructure as active mediation established in Section 2. Three central analytical contributions emerge from the findings, each supported by the convergence of teacher reports, independently collected infrastructural data (school head questionnaire and on-site checks), and contextual alignment with national patterns [CETIC.BR, 2025].

First, the "automatic incorporation of impossibility" (School A) exemplifies how prolonged scarcity not only constrains practices but may also consolidate preconscious cognitive dispositions [Bourdieu, 1977] that reconfigure the very schemes of pedagogical thought. The simultaneous compromise of both teacher and student digital literacies documented in this school suggests a vicious cycle of exclusion that challenges assumptions about universal digital competencies: delayed provision encounters not only unprepared teachers [Gatti *et al*., 2019] but also students lacking the elementary literacies necessary for effective pedagogical use, indicating that policies should consider the prior development of basic competencies as a foundation for material investments.

Second, the functional inversion pattern between Schools B and C suggests that, in the studied contexts, formal resources do not necessarily linearly convert into perceived pedagogical capabilities without enabling conversion factors such as connectivity. As detailed in Section 3.1, the connectivity classifications underpinning this argument reflect reported and observed functionality rather than objectively measured performance metrics; the pattern is grounded in teachers consistently identifying connectivity stability as the binding constraint on their pedagogical capability, an identification corroborated by the independently collected infrastructural data summarized in Table 1. Observational or performance-based data would be needed to establish this as a validated systemic difference.

Even so, the pattern lends empirical plausibility to ecological perspectives on active mediation and resonates with what Toyama [2015] theorizes as the "Law of Amplification": technology amplifies underlying institutional capacities, improving outcomes where systems are functional but producing minimal impact where they are dysfunctional. This non-linearity is further illustrated by the adaptive paralysis tentatively identified in Section 4.2.1: in School B, physically present resources maintain the expectation of technological use without fully enabling it, a dynamic that finds theoretical resonance in Cuban [2001], who documents how institutional environments can sustain reform expectations while constraining the conditions for their realization. This aligns with Ertmer and Ottenbreit-Leftwich [2010], who argue that even knowledgeable teachers may not take pedagogical risks when school cultures fail to support them. This configuration is associated with the development of direct digital appropriations but appears to discourage the emergence of systematic analog alternatives [Certeau, 2014] such as those observed in School A. The anticipatory avoidance documented in Section 4.1.1 suggests that this configuration may operate differently from severe scarcity: rather than stimulating adaptive bricolage through predictable impossibility, partial adequacy may generate a tension between institutional expectations and material limitations that constrains, without eliminating, teacher agency [Priestley *et al*., 2015]. However, pre-existing teacher profiles, institutional cultures, and the specific curricular demands of a technical school may also mediate this pattern, and the mediating factors discussed at the close of Section 4.1.2 apply throughout this analysis.

Third, these two patterns jointly point toward a reconceptualization of the very concept of "access" in educational technology policies. Effective pedagogical access is not reducible to the physical presence of devices; it appears to require a convergence of operational technical functionality, temporality compatible with learning rhythms, and institutionally supported teacher agency [Priestley *et al*., 2015]. The absence of any of these dimensions may compromise the entire system, transforming nominally available resources into unrealizable potentialities. Current approaches to evaluating educational infrastructure often reflect a logic of commodification [Birch and Muniesa, 2020] in which infrastructure is audited by indicators that transform it into a countable asset, rather than by its effective pedagogical impact. The three documented configurations illustrate qualitatively distinct modes of ineffectiveness that aggregate metrics fail to capture: severe scarcity (School A) produces a cognitive incorporation of impossibility; abundant resources with restricted functionality characterize limited adequacy (School B); and competition for access under conditions of network and lab saturation (School C) requires temporal orchestration that limits pedagogical spontaneity. Uniform policies tend to obscure these qualitatively distinct constraints [Selwyn, 2021].

The convergence with recent national diagnoses [CETIC.BR, 2025; Vasconcelos *et al*., 2021] lends plausibility to the hypothesis that similar dynamics operate in other contexts of Brazilian public education, though the documented relationships are associative and the provisional typology constitutes a heuristic analytical tool rather than a validated predictive model. The boundaries of this typology's applicability are examined in Section 5.6.

5.2 Teacher Education: Stratification, Generational Inversion, and Privatization of Responsibilities

The patterns documented in Sections 4.2.2 and 4.2.3 converge with established national diagnoses [Gatti *et al*., 2019; Cardoso *et al*., 2021]. Still, they advance by specifying three patterns that illuminate the persistence of teacher education fragmentation even in the face of universalization efforts: stratification by complementation, stratified teacher education expectations, and selective technology appropriation as a professional survival strategy.

Stratification by complementation designates a dynamic in which schools with greater organizational capital supplement basic universal teacher education with additional capacity-building, creating inequalities between schools that have had access only to the same basic teacher education opportunities. The contrast between School C (which receives additional AI teacher education) and School A (which relies on the inadequate universal offering) empirically illustrates this pattern. Policies that guarantee only a minimum teacher education requirement paradoxically create an illusion of formal equity while reproducing existing hierarchies. This dynamic aligns with communities of practice [Lave and Wenger, 1991] but exposes a problematic dimension: informal networks form as a compensatory response to institutional gaps, rather than as a complement to an adequate teacher education base.

Teacher learning from family members and students (Section 4.2.3) highlights a systemic gap that is compensated for by informal networks. The absence of this generational inversion in School A is particularly telling: infrastructural precarity simultaneously compromises both teacher and student digital literacies, preventing even informal networks from compensating for institutional failures. This normalization of informal dependence appears systemic rather than exceptional, exposing the magnitude of the gap in institutional teacher education programs.

The stratified teacher education demands documented in Section 4.2.2 show how distinct material contexts shape not only practices but also possible horizons of professional development. This stratification, from elementary needs (School A) to advanced technical competencies (School C), appears structural rather than contingent: contexts of scarcity may limit even the ability to imagine sophisticated uses, while adequate infrastructure appears to expand professional repertoires and ambitions. Paradoxically, the only cross-cutting convergence among the three groups (the need for AI teacher education) manifests at qualitatively different levels: basic instrumental use in School A, pedagogical application in School B, and advanced customization in School C. Teacher education policies that ignore these differences reinforce inequalities by offering uniform content to teachers with heterogeneous needs.

The teachers' ability to filter out inadequate teacher education content constitutes a competency forged by adversity, not a desirable pedagogical choice. The abandonment of decontextualized courses is not due to disinterest, but rather "informed resistance" based on a rational cost-benefit assessment by overworked professionals. By transferring this responsibility to the individual, the "system privatizes" costs that should be public [Ball, 2009; Shiroma, 2018], transforming self-directed learning into a professional survival strategy.

5.3 Teacher Agency in Constrained Contexts: Recognition without Romanticization

The documented adaptive strategies foreground a fundamental tension between recognizing genuine professional competencies and the risk of romanticizing structural precarity. Techno-pedagogical bricolage exemplifies the tactics of Certeau [2014] that value teacher autonomy over logics of compulsory adoption [Pretto, 2022]. The teacher who recreates Kahoot in an analog format demonstrates sophisticated literacy, but the emphasis on "*I have to manage*" (P5-A) indicates that this is not a well-founded pedagogical choice but a compulsory response to material impossibility. Recognizing this competency is essential for professional valuation, but celebrating it without simultaneously criticizing the conditions that make it necessary constitutes a romanticization of precarity that obscures systemic fragility and justifies underfunding [Oliveira and Pereira Junior, 2020; Ball, 2009; Shiroma, 2018].

The capability approach of Sen [1999] resolves this tension by distinguishing between capabilities (what people achieve) and conversion factors (the resources that enable these achievements). Adaptive tactics are genuine capabilities, but their necessity highlights the inadequacy of conversion factors. As documented in Section 5.1, the functional inversion pattern illustrates this principle: abundant resources do not necessarily convert into pedagogical capability without enabling conversion factors, and the distinct adaptive strategies across ecosystems reflect environmental configurations rather than portable individual attributes.

Priestley *et al*. [2015] demonstrates that agency arises from the interaction between teachers and their environments, not from abstract individual capacities. The three ecosystems illustrate this principle: School A develops bricolage as a tactical response [Certeau, 2014] when predictable scarcity makes this competency functionally necessary; School B does not develop equivalent analog conversion tactics because partial inadequacy, characterized by available equipment with inadequate connectivity, appears to discourage the systematization of alternatives while enabling a distinct pattern of direct digital appropriation; School C develops temporal orchestration because better proportional adequacy and a full-time schedule create a new constraint (coordination of multiple simultaneous accesses). These differences reflect environmental configurations that enable or block specific types of agency. Agency is always "agency in context," not a portable attribute.

This ecological understanding generates three implications. First, it is necessary to recognize situated knowledge without romanticizing its necessity, incorporating adaptive strategies into official teacher education programs, while also providing an explicit critique of the conditions that give rise to them. Second, investments must expand systemic conversion factors, creating environments for chosen innovation, not compulsory adaptation; reflective agency (such as a teacher's choice not to use an available technology) is only possible when access is guaranteed. Third, it is necessary to redistribute privatized costs, such as self-directed learning time, personal resources, and emotional burden, which are borne individually by teachers. Policies should make these costs visible, measure them, and compensate for them through subsidies, paid time for professional development, and career recognition. The goal of equitable policies is not to perpetuate adaptive heroism but to create contexts where competence manifests as chosen pedagogical innovation.

5.4 Emerging Technologies and Digital Citizenship: Systemic Gaps

5.4.1 Ambivalent Appropriation with Pragmatic Experimentation

The patterns documented in Section 4.3.1 reveal that teacher appropriation of AI constitutes a compulsory reconfiguration that is qualitatively distinct from previous technology integrations. Unlike tools mediated by school infrastructure, AI penetrates via students' personal devices regardless of institutional policies, forcing pedagogical adaptation without adequate preparation. This technological shift fundamentally reconfigures pedagogical relationships [Williamson and Komljenovic, 2023], challenging established assumptions about authorship and assessment while transforming the material conditions of teaching practice [Orlikowski, 2007].

The documented ambivalent appropriation differs from resistance patterns that emerge when technological change is externally mandated without teacher participation [Fullan, 2016]. The data point to a specific configuration, with the explicit and simultaneous recognition of benefits and risks that does not impede functional experimentation but manifests as verbalized critical vigilance during use. This combination (functional experimentation with explicit operational criticality) characterizes a mature technology appropriation that reflects the emergence of professional agency through interaction with material and institutional environments [Priestley *et al*., 2015], suggesting that pragmatic ambivalence, as a discursive and operational pattern, may offer a more productive analytical lens than models that presuppose either uncritical adoption or categorical resistance [Selwyn, 2021].

This appropriation is distinct from established constructs in the technology adoption literature. While Ertmer and Ottenbreit-Leftwich [2010] suggest that technology adoption relies on "value beliefs" — where perceived benefits must outweigh the costs — the pattern observed here points to a pragmatic simultaneity: teachers integrate AI because it addresses concrete professional demands (such as preparing lesson materials, creating activities for different student levels, and optimizing planning under time constraints), despite maintaining a high perception of risk. Its specificity lies in four dimensions. The first is the simultaneity in recognizing potentialities and risks, which coexist without resolving into a single overall assessment; the second is systematic experimentation despite reservations; the third is a functional orientation driven by concrete pedagogical needs; and the fourth is verbalized vigilance as operational reflexivity during use. This configuration suggests a modality of technological agency that requires teacher education policies enabling teachers to productively navigate ambivalence as a permanent condition of teaching in rapidly transforming contexts.

The contrast between the discursive patterns observed across schools also extends the mediating role of infrastructure beyond material practices. In School A, where scarcity limits both pedagogical use and professional development opportunities, teachers' discourse about AI emphasized potentialities without articulating risks, a pattern that differs markedly from the explicit critical vigilance verbalized in Schools B and C. This discursive divergence, however, need not reflect differences in teachers' actual critical capacities. The differentiated access to in-service professional development documented in Section 4.2.2 offers a more empirically grounded explanation: while the State Secretariat of Education provided a single AI-focused training session uniformly distributed across the three schools in the last 12 months, School C autonomously organized an additional and more substantial AI-specific training, positively evaluated by its teachers, whereas School A teachers had access only to the centralized minimum, and within that minimum two participants did not attend at all. Teachers in contexts with greater infrastructural and organizational adequacy thus had access to more diversified professional development trajectories, which may provide the discursive repertoires (vocabularies of critique, risk-benefit framing, reflective distancing) through which ambivalence is articulated. In scarcity contexts, the aspirational framing of AI as a compensatory resource may itself constitute a situated response to structural deprivation rather than an indicator of uncritical adoption. The methodological design of this study, based on focus group discourse rather than direct observation of practice, captures how teachers talk about AI, not how they engage with it (the contrasting discursive patterns across schools are detailed in Section 4.3.1). The well-documented tendency of group settings to amplify normative postures further warrants caution in interpreting these contrasts as differences in critical engagement.

The case of AI appropriation as an assistive technology for neurodiversity (Section 4.3.1) reveals a dimension generally neglected in discussions that focus exclusively on pedagogical productivity. The use for work organization by a teacher with ADHD suggests that emerging technologies operate as tools of cognitive accessibility, a perspective that requires attention in inclusion and universal design policies [Burgstahler, 2015]. This individual case contrasts with institutional policies that rarely consider accessibility, externalizing the discovery of assistive solutions to teachers.

Williamson and Komljenovic [2023] and Birch and Muniesa [2020] situate this transformation within the political economy of educational platforms, demonstrating how they operate the commodification of pedagogical interactions, transforming learning data into monetizable assets. The documented tension between optimization and precarization via productive intensification replicates findings from meta-analyses on AI in higher education [Bond *et al*., 2024]. Crucially, this technology appropriation occurs in a context of systemic teacher education gaps in digital citizenship, compromising the critical competencies necessary for responsible use.

The persistence of basic technological non-appropriation, as documented through the participation of two teachers who are unaware of widely publicized tools, suggests that teacher education gaps extend beyond pedagogical decontextualization, indicating institutional failure. Non-participation in the only AI teacher education offered in 12 months suggests structural barriers (double shifts, perception of irrelevance) that policies rarely address. This finding problematizes narratives about the "universal penetration" of AI: the compulsory pedagogical reconfiguration operates unequally, aggravating professional stratification between teachers with and without access to professional development networks.

5.4.2 Fragmentation of Digital Citizenship Education

The disjuncture between teacher consensus on students' critical inability (Section 4.4.1) and fragmented pedagogical work (Section 4.4.2) exposes a systemic contradiction between diagnosis and intervention that demands a theoretical analysis of the structural causes of its persistence. The literature on curriculum implementation [Cuban, 2013; Fullan, 2016] identifies a recurring gap between policy prescriptions and daily practices, but the case of digital citizenship presents specificities that aggravate this disjuncture: it is a cross-curricular competence that requires multiscalar coordination (national, institutional, teacher) that is nonexistent in the investigated configurations.

As documented, the dependence on individual initiatives shows that the prescribed curricular progression has remained aspirational. Three structural factors emerge from the data as contributing to this implementation gap: the absence of accountability mechanisms connecting prescriptions to effective practices; the lack of specific institutional resources to enable cross-curricular implementation; and the externalization of responsibility to individual teachers without structural support.

This fragmentation reproduces, at the pedagogical level, the dynamics described by theories of second-order digital inequality[5] [Hargittai, 2002; van Dijk, 2020]. The proposal in van Dijk [2020] suggests that access is not limited to equipment possession (material access), but is preceded by user interest (motivational access) and must be supported by digital skills (skills access), ultimately culminating in the effective application of technology in real-world situations (usage access). The findings show that material inequalities (inadequate infrastructure in School A) are associated with skills inequalities (the absence of basic technical literacies) and, in the documented patterns, with the absence of second-order critical literacies necessary for full digital citizenship. Hargittai [2002] argues that contemporary digital inequalities manifest not only in access but in the quality of use, which is precisely what the data document: students in privileged contexts receive structured education in digital citizenship (a formal discipline in School C), while students in scarcity remain dependent on episodic interventions based on individual teacher initiative (School A).

In contexts of severe scarcity, the documented patterns are consistent with a theoretically significant cascading exclusion. The sequential articulation (lack of infrastructure → non-development of technical competencies → preclusion of critical literacies) aligns with what van Dijk [2020] calls cumulative exclusion, in which deprivations in earlier stages of digital access constrain possibilities in subsequent stages. Public policies that prescribe advanced competencies without recognizing this fundamental hierarchy are not only ineffective but also reproduce epistemic violence by holding students accountable for structurally imposed gaps. This dynamic frontally contrasts with principles of educational equity, revealing how universal prescriptions operate unequally in materially stratified contexts.

Why does fragmentation persist despite the consensus on its ineffectiveness? The analysis of the documented patterns suggests three systemic causes. First, the isolated disciplinary approach (a specific Digital Citizenship course) contradicts the cross-curricular nature of the competence: critical digital literacies require contextualized application in specific disciplinary epistemic practices, not abstract and decontextualized treatment. Second, concentration in a specific component externalizes a collective responsibility, allowing other teachers to consider the topic "*already covered*". Third, dependence on individual motivation without institutional support results in a pedagogical lottery: only students assigned to engaged teachers receive adequate instructions, transforming a curricular right into a contingent privilege.

The documented dependence on individual initiatives produces critical theoretical and practical consequences for equity. Theoretically, it contradicts the assumption that a national curriculum serves as a guarantor of universal learning rights. If implementation depends on idiosyncratic variables (such as teacher engagement and institutional capital), national prescriptions operate as normative fictions without material substance. Practically, this dependence stratifies teacher education opportunities according to cultural and institutional capital: schools with greater adequacy formalize curricular components (School C), while contexts of scarcity remain in reactive interventions (School A). Consequently, students face a cumulative double inequality — material and formative.

In contrast to the documented punitive-reactive approaches (Section 4.4.3), preventive-educational perspectives [Livingstone and Third, 2017] emphasize student agency and understanding of consequences, not external control. The theoretical implications of this distinction are profound: punitive approaches reproduce disciplinary conceptions of education that constrain critical autonomy, while preventive approaches develop the deliberative capacities necessary for democratic participation. The findings indicate that the investigated schools primarily operate under a punitive logic, thereby wasting pedagogical opportunities to transform digital conflicts into substantive learning experiences about ethics, empathy, and collective responsibility.

5.4.3 Intersection between AI and Digital Citizenship Gaps

The ambivalent appropriation of AI and the fragmentation of digital citizenship education, treated analytically as distinct phenomena, intersect empirically in a critical way: the absence of critical digital competencies aggravates the risks associated with pragmatic experimentation with AI. Teachers who use AI functionally (Schools B and C) verbalize concerns about reliability and inadequate student use — concerns that demand precisely the critical literacies whose absence was consensually diagnosed (Section 4.4.1). This intersection exposes a systemic contradiction: teachers are being compelled to adapt to a disruptive technology without students developing the competencies to navigate it critically.

The implications of this intersection transcend the sum of isolated gaps, configuring a magnified vulnerability. Students who use AI as "*an end, not as a means*" (Section 4.3.1), without the ability to assess the reliability of sources critically evaluate the potential distortions of AI-generated outputs, face qualitatively different risks from those of previous generations: dependence on tools whose outputs remain unreliable and difficult to evaluate without specialized domain knowledge. The critical competencies prescribed by the BNCC Computing [Brasil, 2022] (Section 4.4.1) for evaluating digital information and identifying biases in electronic sources are precisely those whose absence aggravates this vulnerability. The lack of critical education on these technologies not only limits learning but also shapes cognitive dispositions that lead to uncritical acceptance of algorithmic authority, contradicting democratic principles of autonomy and deliberation.

Public policies that address AI and digital citizenship separately fail to recognize this constitutive interdependence. Effective recommendations must integrate educational programs on critical digital literacies with the development of specific competencies for evaluating emerging technologies, overcoming a fragmentation in policies that replicates the same disarticulation documented in school practices.

[5] The digital inequality literature distinguishes between first-order inequality (access to devices and connectivity), second-order inequality (differences in skills and usage patterns among those with access) [Hargittai, 2002], and third-order inequality (unequal tangible outcomes derived from technology use) [van Dijk, 2020].

5.5 Implications for Public Policy: Evidence-Based Recommendations

The findings generate four specific recommendations derived directly from the documented patterns, organized by the strength of the empirical evidence and the feasibility of implementation.

1. **Prioritize Connectivity Where Equipment Already Exists:** The functional inversion pattern (Section 4.1.1) indicates that, in the studied contexts, teachers perceived connectivity as the binding constraint on pedagogical capability: **School B**, with a larger physical endowment, was reported by teachers as having lower pedagogical functionality than **School C**, a difference that participants attributed primarily to inadequate connectivity, though institutional factors may also contribute. For schools that already possess equipment but lack adequate connectivity, it is recommended to conduct a technical audit and prioritize investments in network infrastructure before new hardware acquisitions. Establishing minimum connectivity as an adequacy criterion and redirecting resources to fix networks in schools with underutilized equipment maximizes investments already made with high implementation feasibility. For schools lacking both equipment and connectivity, integrated provision addressing both dimensions simultaneously is necessary, since connectivity alone does not compensate for the absence of devices. More broadly, evidence from similar contexts indicates that providing equipment without ensuring the conditions for its effective pedagogical use can widen pre-existing educational inequalities [Rodriguez-Segura, 2022], reinforcing the need for needs-specific rather than uniform provision strategies.
2. **Ensure Operational Conditions for Lab-Based Technology Use:** The temporal constraint documented in Section 4.1.1 indicates that, in the absence of dedicated logistical support, the setup time for mobile labs consumes a disproportionate part of the class. The same evidence shows that when institutional orchestration is provided (schedule adjustments, mobilization of multiple staff members, redistribution of responsibilities), these temporal constraints are absorbed, suggesting that the barriers are primarily operational rather than inherent to the mobile format. However, such orchestration was documented only during exceptional institutional activities and is not available for everyday pedagogical initiatives within the current operational structure of the state educational system. Fixed labs eliminate per-session setup costs and offer predictable operational conditions without requiring additional support infrastructure, making them the more viable option under existing conditions. Where fixed labs exist or can be created, their expansion or maintenance is recommended. For schools where mobile labs constitute the available equipment, feasible measures within the current structure, such as pre-charging protocols, designated storage adjacent to classrooms, and simplified distribution routines, can reduce, though not eliminate, the temporal burden on individual teachers.
3. **Implement Basic Digital Literacy as an Operational Prerequisite:** The pattern of cascading exclusion documented in Sections 4.1.1 and 4.4.1, characterized by the absence of elementary digital literacies in both teachers and students, creates operational bottlenecks that prevent the use of existing infrastructure. It is recommended to implement a mandatory basic digital literacy module in the first few weeks of the school year for students, covering access with institutional credentials, platform navigation, password management, and elementary criteria for reliable sources. In schools where infrastructure is not yet operational, the BNCC Computing curriculum [Brasil, 2022] provides a viable pathway through its explicit provision for unplugged activities, enabling the development of these competencies independently of technological resources. Law No. 15,100/2025 [Brasil, 2025a], which restricts personal mobile devices in schools, reinforces the urgency of this institutional provision: with the informal pathway through students' own devices now foreclosed (Section 4.3.1), school-provided instruction becomes the only remaining route to student digital competence, transferring to the school system a formative responsibility that previously could be partially absorbed by informal uses of personal devices. For teachers, the mandatory basic course should cover the operation of school equipment, use of institutional platforms, and connectivity management. This measure has high feasibility as it requires low cost and only pedagogical coordination. Its effectiveness, however, presupposes minimally operational infrastructure; where this condition is not yet met, the literacy module should prioritize unplugged computing strategies and competencies that will be immediately applicable once operational conditions are established.
4. **Redesign in-service teacher education with a Focus on Modularization and Contextualization:** The systematic teacher education inadequacy documented in Section 4.2.2, evidenced by the universal dependence on self-directed learning and the development of selective technology appropriation as a survival competency, indicates a structural failure of current offerings. It is recommended to structure in-service teacher education into short modules focused on specific pedagogical problems, each including a practical demonstration and explicit adaptation for different infrastructural configurations. Offering these in multiple formats, combined with an organized repository, enables teachers to select options according to their specific needs. This measure has moderate feasibility as it requires redesigning the current model.

Effective implementation should follow a logical sequence that recognizes dependencies. In the immediate phase, a connectivity audit and basic digital literacy education establish operational foundations. In the short term, prioritize connectivity fixes and redesign in-service teacher education to consolidate capabilities. In the medium term, prioritizing fixed labs in new acquisitions completes the cycle of infrastructural adequacy. These four recommendations represent those we were able to formulate from the patterns observed in three urban schools within a specific context. Broader recommendations require dedicated investigations before being prescribed. Their implementation, however, is not merely a matter of technical execution: the systemic conditions analyzed in Section 5.1, particularly the disconnect between formal resource availability and effective pedagogical functionality, suggest that the same structural patterns that generated the documented problems are likely to constitute barriers to their resolution.

5.6 Study Limitations and Future Directions

This study has limitations that define the scope of its contributions and signal directions for subsequent investigations. First, the analysis focuses on three urban schools within a specific geographical context, which limits the direct transferability of the findings to rural environments, where infrastructural challenges are generally more severe. Second, the absence of direct classroom observations limits understanding to teacher reports, failing to capture actual practices that may diverge from discourse. Third, the cross-sectional design is a critical limitation for causal inferences. Although we have identified associations between infrastructural configurations and technology appropriation patterns (e.g., scarcity associated with the incorporation of impossibility; technical inadequacy associated with the fragmentation of competencies), the causal direction remains inferred rather than empirically demonstrated. Specifically, the observed relationship between infrastructural scarcity (School A) and the development of techno-pedagogical bricolage, in contrast to direct technology appropriation in School B, suggests an associative pattern that requires qualification.

Other factors not controlled for in this study may mediate this relationship: pre-existing teacher profiles, the specific institutional culture of each school, differentiated teacher education trajectories of the teachers, or local school management policies.

Additionally, voluntary recruitment may have introduced a selection bias, over-representing teachers with a predisposition to technological engagement and under-representing dimensions of genuine resistance, non-appropriation, or abandonment. Validating causal relationships requires longitudinal studies that track the development of adaptive competencies in response to infrastructural changes over time. For instance, it would be necessary to document whether teachers who develop bricolage in contexts of scarcity maintain, adapt, or abandon these strategies when infrastructure improves, or if teachers transferred from abundant to scarce contexts progressively develop the same adaptive tactics. The cross-sectional design also impedes the temporal analysis of technology appropriation processes, a particularly relevant dimension for rapidly evolving technologies like AI.

Potentially relevant aspects remained underexplored in this investigation. The variation in technology appropriation by gender (15 men, 10 women in total) was not systematically analyzed. Emerging phenomena (Section 4.2.4), such as the commercialization of ready-made digital pedagogical materials and the use of personal devices for pedagogical management, signal contemporary dynamics — the commodification of educational resources and the privatization of institutional costs — that require dedicated investigation for a deeper understanding of their systemic implications.

Finally, the scope's delimitation to regular, integrated technical, and full-time high school deliberately excluded Youth and Adult Education (EJA) and subsequent professional education. Both modalities have curricular and student profile-specificities that merit dedicated investigation and cannot be treated as variants. The transferability of the findings should, therefore, be circumscribed to the investigated formats.

Given this, three future directions emerge as priorities. First, longitudinal studies that follow teachers during infrastructural changes (e.g., implementing connectivity in schools with severe scarcity) would allow for testing causal relationships between material configurations and the development of adaptive competencies, adjudicating between alternative interpretations presented in this study. Second, a dedicated investigation on AI appropriation should include: (a) collaborative development with teachers of situated ethical frameworks for pedagogical use; (b) analysis of impacts on teacher workload, distinguishing genuine optimization from masked intensification; (c) a longitudinal study on how technology appropriation evolves as tools mature and teachers develop specific literacies. Third, research on the invisible costs of technological teaching work — quantifying the time spent on self-directed learning, investment in personal resources (such as equipment, connectivity, and software), and the emotional burden of navigating constrained contexts — would inform policies for recognition and adequate compensation. These directions would benefit from collaborative designs that position teachers as co-investigators, rather than objects of study, thereby generating knowledge more relevant to the transformation of educational practice.

A fourth direction concerns the operationalization and scaling of the proposed typology. The current typology, derived from qualitative analysis of three urban schools, could be refined for broader application through complementary instruments. Quantitative surveys incorporating scales designed to capture connectivity quality (beyond binary availability), effective equipment accessibility (distinguishing nominal from functional access), and temporal constraints on technology use could enable preliminary classification of schools into ecosystem types at scale. Structured observation protocols documenting actual technology use patterns, setup times, and failure rates would provide behavioral data complementing teacher self-reports. Additionally, where institutional platforms are operational, learning analytics (access logs, usage frequency, session duration) could offer objective indicators of technology integration intensity. Mixed-methods designs combining these instruments with focused qualitative investigation in strategically selected schools would enable both validation and refinement of the typology across the diverse contexts identified as limitations earlier in this section, including the rural settings, additional geographic regions, and excluded educational modalities discussed above. Each of these extensions constitutes a distinct empirical question rather than a presumed generalization.

6 Conclusion

This study investigated how teachers appropriate educational technologies in contexts of heterogeneous infrastructure, documenting that different material configurations are associated with qualitatively distinct fields of pedagogical possibilities. A qualitative investigation involving 25 teachers from three urban schools in Pernambuco state educational system yielded provisional patterns that transcend the simplifying dichotomies between technological adequacy and inadequacy.

In response to the four research questions, we documented that (RQ1) distinct infrastructural configurations mediate teacher technology appropriation through three techno-pedagogical ecosystems (Survival, Limited Adequacy, and Competition), each with its own operational logic, with connectivity being identified as a perceived critical conversion factor; (RQ2) teachers develop differentiated adaptive strategies according to their material contexts, including techno-pedagogical bricolage in severe scarcity, documenting a reflective agency that operates through creative tactics; (RQ3) the appropriation of AI manifests through contextualized modes, with cases articulating ambivalent appropriation with pragmatic experimentation in contexts of greater adequacy, while scarcity was associated with a discourse of technological optimism; (RQ4) digital citizenship remains fragmented, depending on individual initiatives without institutional support.

The proposed typology of techno-pedagogical ecosystems moves beyond quantitative metrics by capturing qualitatively distinct operational logics, illustrating the analytical applicability of ecological perspectives in specific contexts of Brazilian public education. In this sense, the identification of connectivity as a perceived critical conversion factor and the documentation of a functional inversion pattern between material adequacy and reported pedagogical capacity challenge linear assumptions about the provision of technology. Complementarily, the characterization of ambivalent appropriation with pragmatic experimentation offers a conceptual alternative to dichotomies between technophilia and technophobia. From a methodological standpoint, we also illustrated the feasibility of Framework Analysis for systematically comparing multiple sites in qualitative educational investigations.

In light of these findings, we identified four interventions for educational technology policies, hierarchized by feasibility: first, prioritize connectivity for schools with existing but underutilized equipment (based on the functional inversion pattern); second, ensure operational conditions for lab-based technology use, favoring fixed labs under the current operational structure of state schools (responding to temporal constraints); third, implement basic digital literacy as a prerequisite (addressing the documented pattern of cascading exclusion); and fourth, redesign in-service teacher education with contextualized modularization. It is essential to note that acknowledging teacher agency without romanticizing precarity implies that policies must value the competencies developed, while expanding the conversion factors that enable the appropriation of technology as a chosen innovation, rather than a compulsory adaptation.

As discussed in Section 5.6, the concentration on three urban schools and the cross-sectional design limit transferability and preclude causal inferences, though the convergence with national diagnoses lends plausibility to the hypothesis that the identified patterns represent local manifestations of broader systemic dynamics.

Returning to the central empirical findings, the teachers investigated demonstrate professional competencies forged in constrained contexts, developing pedagogies through creative tactics and a critical appropriation of digital technology. This proactive role deserves institutional recognition, but should not obscure structural inadequacies nor transfer systemic responsibilities onto individual capabilities. On the contrary, the effective transformation of techno-pedagogical ecosystems requires an articulation between infrastructural adequacy, contextualized teacher education, the development of critical literacies, and a reorganization of teaching work that acknowledges currently externalized costs.

In summary, the quality of public education in technologically mediated contexts cannot be reduced to the availability of equipment. Still, it is constituted by the convergence of functional infrastructure, robust teacher education, adequate working conditions, and the recognition of teachers' pedagogical agency. As documented in this investigation, different infrastructural configurations do not merely hinder or facilitate the appropriation of technology. They shape which types of teacher agency become possible, necessary, or blocked. Therefore, equitable policies cannot perpetuate contexts that demand adaptive heroism for basic functioning but must create environments where competencies manifest as chosen pedagogical innovation, not as compulsory survival amidst structural precarity.

Declarations

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Use of AI Tools. Google Gemini (versions 2.5 Pro and 3.0 Pro) was used for three purposes during the preparation of this manuscript: (1) initial automated transcription of focus group audio recordings, as described in Section 3.4; (2) orthographic and stylistic revision of the manuscript text; and (3) assisting in the translation of the manuscript from Portuguese to English. All AI-generated outputs were critically reviewed, verified, and substantially revised by the authors, who assume full responsibility for the accuracy, integrity, and final form of the published content. No AI tools were used for research design, data analysis, coding, interpretation, or the generation of findings.

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Authors' Contributions

Thyago Costa contributed to the conception of this study, data preparation and analysis, and writing of the manuscript. Rodrigo Lins and Taciana Pontual supervised the research and participated in the validation of the study, as well as in the critical review and final editing of the manuscript. All authors read and approved the final manuscript.

Competing interests

The authors declare that they don't have competing interests

Availability of data and materials

The combination of small group sizes, specific disciplinary profiles, and institutional characteristics makes effective anonymization of raw transcripts unfeasible, as the combination of attributes (teaching area, years of experience, school type) could enable identification within the local educational community. For this reason, the raw data cannot be shared. The following materials are publicly available at `https://bit.ly/3NSvYAl` to support transparency and methodological traceability: (a) school head questionnaire; (b) focus group script; (c) supplementation and field notes spreadsheet; (d) initial codebook (32 codes); (e) consolidated codebook (23 codes); (f) consolidation mapping; and (g) analytical matrix.

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