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A Decade of Drone-Based Learning in Primary Education A Systematic Review

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Abstract

Aim/Purpose	Drone technology is emerging as a pedagogical tool in Science, Technology, Engineering, Arts, and Mathematics (STEAM) education, with the potential to foster 21st-century skills. This paper addresses the lack of consolidated evidence by examining global trends and learning outcomes associated with Drone-Based Learning (DBL) within primary education.
Background	Although drones are increasingly integrated into educational contexts, research remains dispersed, methodologically heterogeneous, and often limited to short-term interventions. This review responds to this gap by synthesizing a decade of DBL initiatives in primary schools (2014-2024).
Methodology	Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, we screened 706 records and selected 21 studies focusing on STEAM activities integrating drones in primary education. Data were extracted on pedagogical aims, competencies targeted, assessment methods, and reported outcomes.
Contribution	This review provides a comprehensive, systematic synthesis of DBL in primary education, mapping curricular applications, competency development, methodological trends, and assessment approaches, while identifying structural constraints and distinguishing between field-level and contextual limitations.

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Findings	Across studies, DBL activities were associated with increased student engagement, collaboration, and satisfaction. They reported learning outcomes clustered around technological skills (e.g., programming, computational thinking), transversal competencies (e.g., teamwork, problem-solving), and specific subject domains (e.g., language, environmental education). However, most studies relied on self-reported perceptions, non-standardized assessments, and short-term interventions; only three employed pre/post measurements. These findings indicate that DBL in primary education remains an emerging and not yet consolidated research domain.
Recommendations for Practitioners	Educators implementing DBL should combine drone activities with clear competency-based learning objectives and use diversified assessment tools, such as performance tasks and observations, to capture both procedural and transversal learning.
Recommendations for Researchers	Future DBL studies should adopt more rigorous designs, preferably mixed-methods or longitudinal studies, and apply standardized assessment instruments to enhance robustness and comparability.
Impact on Society	By enabling early engagement with technological and transversal skills relevant to the Fourth Industrial Revolution (4IR), DBL can help reduce digital skill gaps and promote inclusive access to emerging technologies in primary classrooms.
Future Research	Further work should develop standardized evaluation frameworks, interdisciplinary pedagogical models, and longitudinal studies to strengthen the evidence base for DBL and support its scalable integration into primary curricula.

Keywords	drone, learning, primary school, critical thinking, steam

INTRODUCTION

Traditional education, often characterized by unidirectional knowledge transmission, positions students as passive recipients and limits opportunities for experiential, contextually meaningful learning (Lackéus & Williams Middleton, 2015; Liljedahl, 2018). Critical voices such as Hooks (1994) and Giroux (2020) argue that this industrial-age model no longer meets the demands of a rapidly changing society and call for dynamic, holistic approaches that integrate social, cultural, and emotional dimensions into learning. In response, experience-based and technology-enhanced approaches reposition learners as active participants and promote more applied and meaningful learning processes (Coulson & Harvey, 2013; Hanid et al., 2020).

Within this shift, STEAM (Science, Technology, Engineering, Arts, and Mathematics) provides an interdisciplinary framework fostering creativity, collaboration, and critical thinking, competencies aligned with the demands of the Fourth Industrial Revolution (4IR) (Kembara et al., 2019; Trilling & Fadel, 2009). In this context, emerging technologies are increasingly explored as enablers of experiential and applied learning, as reflected in recent initiatives that connect classroom activities with real-world challenges through experiential learning environments (Salinas-Navarro et al., 2024).

Drone technology, specifically Unmanned Aerial Vehicles (UAVs), represents one such emerging tool, offering opportunities to integrate hands-on, interdisciplinary activities into educational settings (Gull et al., 2022; Tezza et al., 2020). It enables real-world applications that can support spatial reasoning, computational thinking, and problem-solving across multiple domains (Hall & Seth, 2022; Yepes et al., 2022), while technology-enhanced, project-based approaches foster engagement and applied learning in STEM contexts (Heng & Jin, 2025; H. Jiang et al., 2025).

In this study, the term "drone" refers specifically to unmanned aerial vehicles (UAVs), the aerial vehicle component of what regulatory frameworks define as unmanned aircraft systems (UAS), aircraft operated without an onboard human pilot and capable of autonomous or remotely controlled flight (European Union Aviation Safety Agency, 2020; Federal Aviation Administration, 2023). While the broader concept of "drones" may include ground-based or wheeled autonomous systems (e.g., educational robotics platforms such as LEGO Mindstorms or FIRST LEGO League robots), this review intentionally focuses on aerial drones due to their distinctive pedagogical affordances. In particular, UAVs enable three-dimensional mobility, aerial data acquisition, and spatial-environmental interaction, which differentiate them from ground-based robotics and support unique applications in areas such as geospatial reasoning, environmental observation, and embodied learning. A more detailed discussion of terminology and classification is provided in the Supplementary Materials, openly available on Zenodo at https://doi.org/10.5281/zenodo.17038756.

However, despite promising outcomes at secondary and higher education levels (M. Y.-C. Jiang et al., 2024), the pedagogical use of drones in primary education remains limited, fragmented, and methodologically heterogeneous. Literature often generalizes about educational benefits without detailing their impact on young learners or aligning with curricular goals (Yeung et al., 2024), and insufficient attention is paid to teacher preparation and pedagogical integration (Hodgson & Piovan, 2022). This lack of consolidation hinders the scalability and sustainable adoption of DBL within early educational settings.

Unlike previous reviews that either aggregate multiple educational levels or focus predominantly on secondary and higher education, this study provides a stage-specific synthesis of DBL in primary education. In addition to mapping existing research, it introduces a pedagogically grounded interpretation of UAV affordances, identifies structural bottlenecks affecting implementation, and explicitly distinguishes between limitations of the research field and constraints inherent to primary education contexts. This combined analytical and conceptual approach enables a more precise understanding of DBL's current state, potential, and scalability in early education.

Therefore, given these gaps, this systematic review synthesizes a decade of research to clarify the scope and educational impact of DBL in primary education, identify key research gaps, and inform future pedagogical and research directions. Accordingly, this systematic review aims to address the following research questions:

- **RQ1**. What is the current scope and educational impact of drone integration in primary school curricula in terms of student engagement, learning outcomes, and skill development?
- **RQ2.** How do DBL methodologies contribute to curricular innovation and social development in primary education?
- **RQ3.** How does drone technology foster essential 21st-century competencies such as self-directed learning, autonomy, personal initiative, entrepreneurship, and communication skills?

Literature Review

Pedagogical benefits of drone-based learning (DBL)

Research consistently shows that drones effectively support experiential, project-based learning within STEM and STEAM contexts, fostering engagement, problem-solving, and real-world application (Bhaduri et al., 2018; Herodotou et al., 2019; Sivenas & Koutromanos, 2022). Their integration enhances spatial reasoning, computational thinking, and interdisciplinary connections (Georgiou et al., 2021) across subjects such as mathematics, geography, physics, and programming (Chou, 2018; Hall & Seth, 2022; M. Y.-C. Jiang et al., 2024).

In primary education, drones make abstract concepts tangible (Clever et al., 2016), a finding supported by early experimental work demonstrating improved long-term retention in subjects such as mathematics, physics, and geography when drones are used as learning tools (Fokides et al., 2017). They nurture the four C's of 21st-century learning: Creativity, Collaboration, Critical Thinking, and Communication (Coulson & Harvey, 2013), while also supporting more specific foundational processes such as spatial reasoning, coordinated decision-making, and structured peer interaction. They also stimulate motivation and exploration, supporting early-stage learning rather than specialized learning. Initial implementations have extended to areas such as physical education (Pergantis & Drigas, 2024) and environmental studies, demonstrating the adaptability of Drone-Based Learning across diverse curricular domains.

Despite a growing body of literature, most reviews to date have focused on secondary or higher education (M. Y.-C. Jiang et al., 2024; Pergantis & Drigas, 2024; Yeung et al., 2024), leaving primary education comparatively underexplored. This reinforces the need for more systematic research on DBL's pedagogical potential and classroom applicability in early learning stages.

Challenges and limitations

Despite their potential, drones face pedagogical and logistical challenges in primary contexts. Teachers often report a lack of training or models for effective integration, and express uncertainty about adapting drones to young learners (Hallifax et al., 2016; Isingizwe et al., 2024), positioning teacher readiness as a central structural limitation. Additional constraints include equipment costs, airspace regulations, and increased supervision requirements (Ilori & Ajagunna, 2020). Moreover, the novelty of drones may overshadow learning if not grounded in solid pedagogical goals (Lackéus & Williams Middleton, 2015). Their successful implementation depends not just on access to technology, but on thoughtful, outcome-oriented design aligned with curricular goals.

Taken together, these findings reveal a tension in the current literature, highlighting a persistent gap between reported pedagogical benefits and the methodological robustness of the evidence base in primary education. This review addresses this gap by synthesizing current evidence on outcomes, methods, and implementation contexts, specifically examining how the unique affordances of UAVs support foundational cognitive schemas during a critical stage of student development where methodological robustness is currently lacking.

MATERIALS AND METHODS

We conducted this systematic review following PRISMA (2020) guidelines in three phases: (1) data collection, (2) screening, and (3) analysis, to synthesize evidence on DBL in primary education and ensure replicability (Gough et al., 2017; Petticrew & Roberts, 2006).

DATA COLLECTION AND SEARCH STRATEGY

We conducted a comprehensive search in Scopus and Web of Science using Boolean combinations related to drones and learning. These databases were selected for their recognized coverage of high-quality, peer-reviewed scientific literature and for their widespread use in systematic reviews, thereby ensuring methodological rigor, consistency, and reproducibility. The term 'drone' is used specifically to refer to UAVs to ensure it aligns with the study's conceptual scope and search strategy. The joint retrieval (March 2025) yielded 16,410 records across formats. We applied database-level filters to the core query (years 2014-2024; document types: articles, proceedings, and reviews; English language; education-relevant subject areas; Scopus/WoS mapping detailed in Table S1).

Records were exported and deduplicated programmatically using DOI and metadata matching to ensure methodological consistency (see Supplementary Materials for details). The combined dataset (n = 746) was reduced to 706 unique records. After screening titles, abstracts, and full texts against pre-specified inclusion dimensions (Educational, STEAM, Artistic, Technological) and exclusion criteria (e.g., non-educational uses, speculative work, no full text), 118 records were assessed in full, and 20 met all criteria (Figure 1). Following the reviewer's suggestion, one additional eligible study, indexed in Scopus, was identified and included using the same inclusion criteria, resulting in a final dataset of

21 studies. Due to database indexing practices, some records were associated with multiple subject areas (e.g., Engineering or Computer Science), which does not affect the inclusion criteria applied in this review (details in Supplementary Materials).

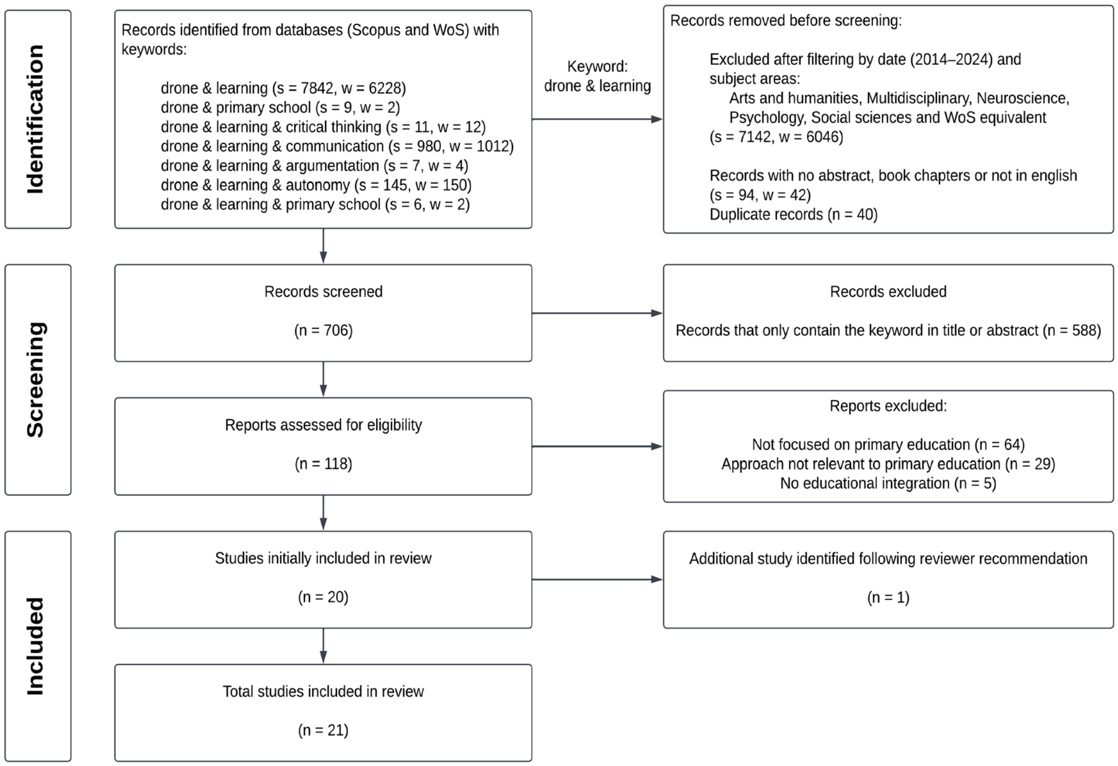


Figure 1. Flowchart of the systematic review process, following PRISMA 2020 guidelines (Page et al., 2021) Data source: Scopus and WoS searches (see Supplementary Tables S1 and S2)

Inclusion/Exclusion Criteria

The inclusion criteria were defined along four research dimensions:

1. Educational: focus on pedagogical models and critical thinking.
2. STEAM: Emphasis on interdisciplinary approaches.
3. Artistic: Inclusion of creative and artistic elements.
4. Technological: Utilization of emerging technologies.

Additionally, studies had to:

- Occur in educational contexts.
- Involve drone technology, specifically UAVs.
- Provide full text and abstract.
- Be accessible in English.
- Published between 2014 and 2024.

Exclusions applied to studies that:

- Lacked educational relevance.
- They were speculative or non-empirical.
- Focused on non-educational applications (e.g., military).
- Had no full-text access.
- Were duplicate records.

The screening followed a three-step process:

1. Initial screening: Title and Abstract review. Excluded studies not related to education, learning processes, or DBL applications.
2. Content screening: Full-text review. Removed publications not meeting relevance or alignment with the research dimensions.
3. Expert validation. An expert panel reviewed the final set of publications, ensuring methodological rigor and empirical depth.

Complementary perspectives, such as Game-Based Learning, Smart Cities, and art-based drone initiatives, were examined through grey literature. Although they provided contextual insights, they lacked the academic rigor for inclusion in the final dataset.

Analysis and Quality Appraisal

We conducted a bibliometric analysis to map trends and themes, using VOSviewer (van Eck & Waltman, 2010) for keyword co-occurrence networks and RStudio with the Bibliometrix package for indicator and thematic analysis. Network analyses applied a minimum threshold of two keyword occurrences and association-strength normalization. Author names and affiliations were standardized to ensure consistency. One of the included studies did not provide indexed or author keywords; therefore, it was not incorporated into the keyword-based analyses.

In parallel, we applied a predefined classification framework aligned with the research questions to categorize contributions into: (1) enhancing curriculum, (2) addressing material gaps, (3) promoting new learning domains, and (4) assessing social and educational impact.

Study quality was appraised using the Mixed Methods Appraisal Tool (MMAT; Hong et al., 2018), applying design-specific criteria for qualitative, quantitative, and mixed-methods studies. Four reviewers assessed each paper independently, and discrepancies were resolved by consensus. A detailed overview of measurement instruments across included studies is provided in Supplementary Table S3. Full parameter settings, software details, and the reproducibility bundle (datasets and analysis scripts) are provided in the Supplementary Materials.

Results

This section presents the results of the systematic review in relation to the previously defined research questions. It examines how Drone-Based Learning (DBL) has been implemented in primary education, focusing on publication trends, thematic structures, and the characteristics of the included studies.

Bibliometric Analysis

The final dataset comprises 21 studies published between 2017 and 2024, reflecting a recent but still limited body of research on DBL in primary education. The evidence base is relatively small and fragmented, with modest international collaboration (15%), suggesting the field is still emerging and not yet established as a mature research domain. The following subsections present key trends in publication output, thematic structures, and research focus.

Annual scientific production

No publications were identified between 2014 and 2016. The first study appeared in 2017 (Palaigeorgiou et al., 2017). A peak occurred in 2018, followed by a decline from 2019 to 2020 and a steady trend thereafter (Figure 2). This suggests early enthusiasm, perhaps driven by increased drone accessibility and interest in STEAM, but no consistent growth over time, indicating that DBL in primary education remains at an exploratory stage.

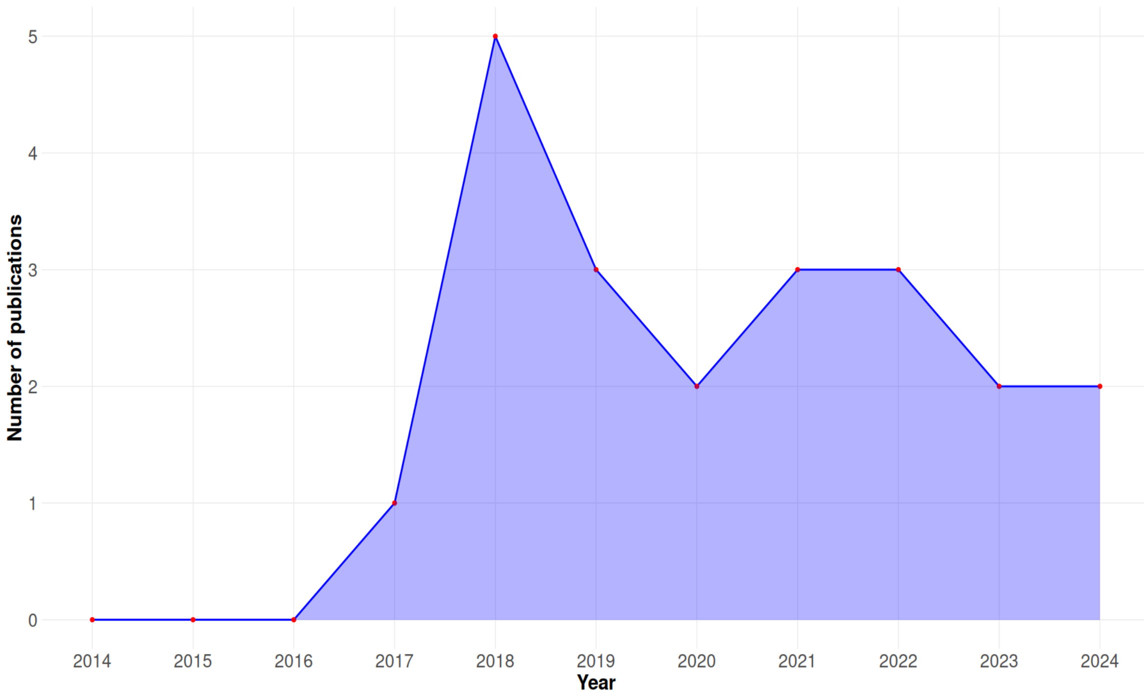


Figure 2. The trend in the number of publications of the Scopus and WoS databases, using R code (amounts calculated over n = 21 included studies)

Subject area and document type

The distribution of subject areas reveals a concentration in Social Sciences and Computer Science, reflecting the dual pedagogical and technological nature of DBL. However, the limited presence of education-specific classifications suggests that DBL remains primarily framed as a technological intervention rather than a fully established pedagogical approach. Most publications are articles and conference papers, reinforcing the field's exploratory and still-developing nature.

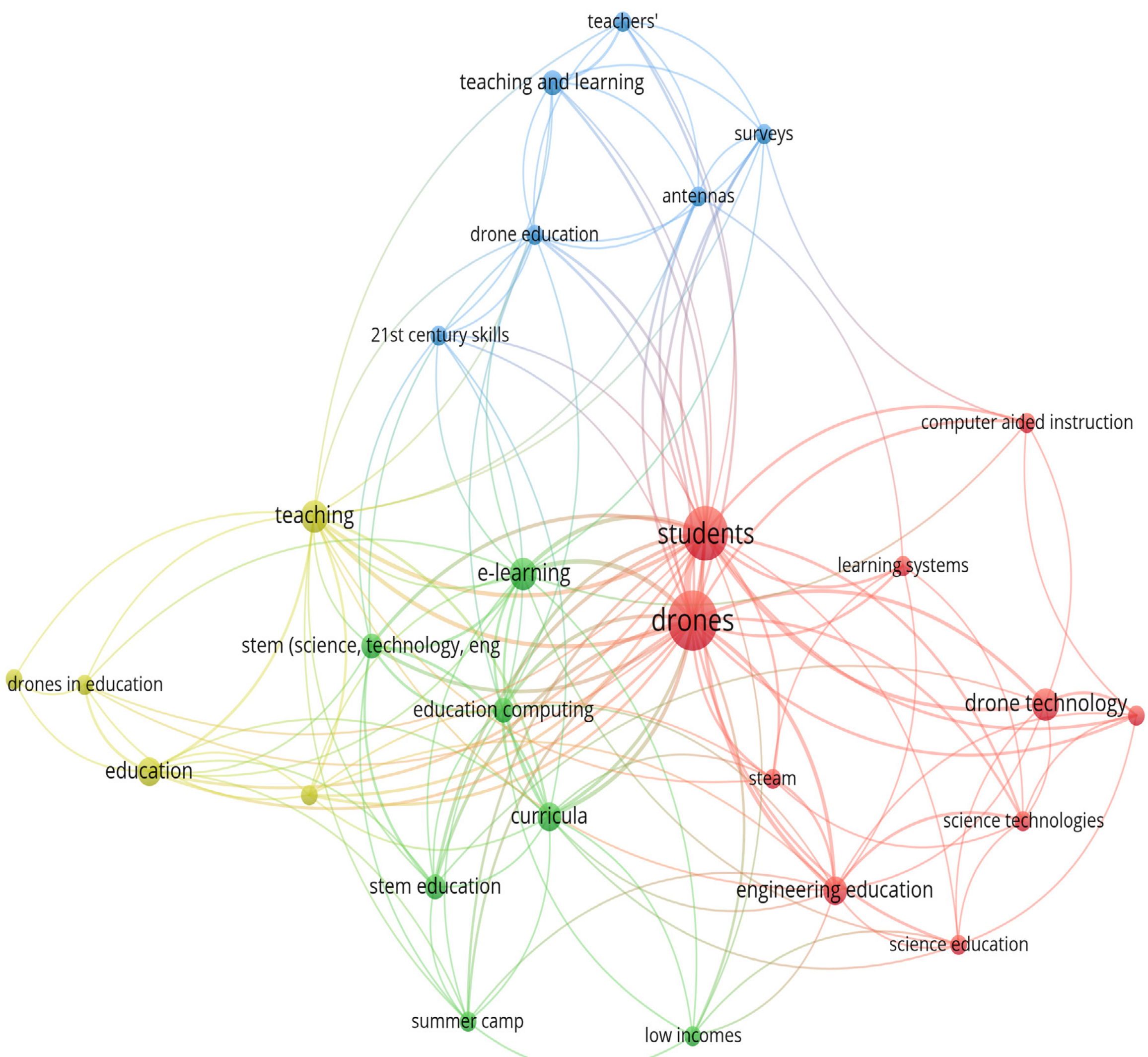
This distribution directly informs RQ1, indicating that current DBL research is primarily framed as a technological and interdisciplinary practice. At the same time, its consolidation as a pedagogically grounded field within primary education remains limited. Detailed distributions of subject areas and document types are available in the Supplementary Materials (Figures S1a, S1b, and S2).

Keywords

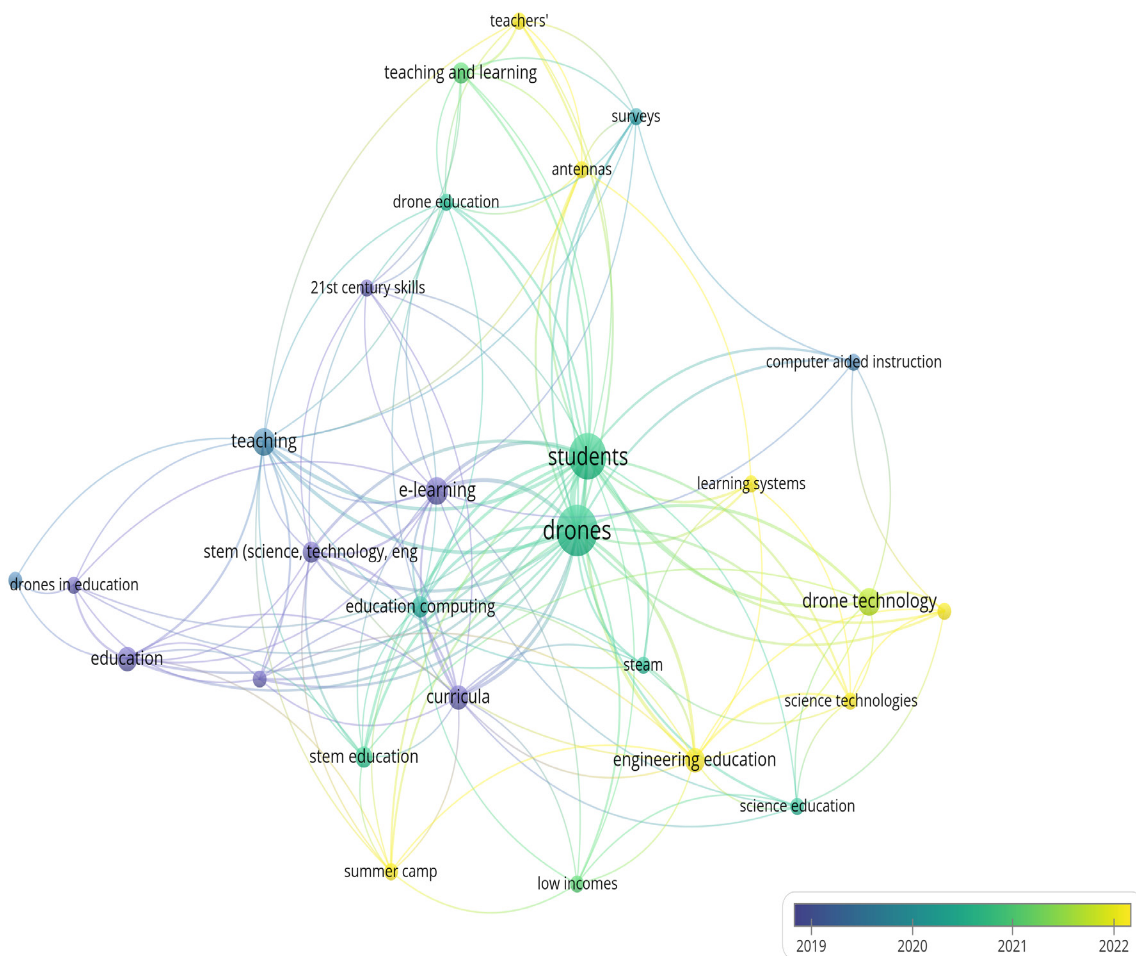
Keyword analysis reveals a strong focus on learning and technology in DBL research. The most frequent terms include "drones" and "students", accompanied by concepts related to STEM education, computational thinking, and e-learning, indicating a concentration on technology-driven and skills-based applications (Table S4). Across all analyses, these central terms reflect a strong emphasis on technological implementation and learner engagement. In contrast, terms such as "curricula" and

"21st century skills" appear less frequently and in more peripheral positions, suggesting that, although frequently referenced, these dimensions remain weakly integrated into the core structure of DBL research. This imbalance indicates that drone-based activities are often introduced as isolated interventions rather than as components of systematically embedded curricular practices. It should be noted that one included study did not provide indexed or author keywords and was therefore not incorporated into the keyword-based analyses.

Co-occurrence analysis identifies clustered thematic structures centered on technology integration and learning processes (Figure 3), with limited diversification beyond STEM-oriented contexts. While this review frames DBL within a STEAM perspective, the keyword results reveal a predominantly STEM-oriented evidence base, where the "Arts" and "Humanities" dimensions remain largely peripheral. This pattern suggests that DBL applications at the primary level remain predominantly anchored in these domains, reinforcing the idea that curricular integration beyond STEM remains underdeveloped. The temporal overlay further indicates a shift from exploratory uses toward more applied educational implementations, particularly in areas such as computational thinking and teacher-related practices.



(a)



(b)

Figure 3. Keyword co-occurrence maps:
(a) clusters of frequently co-occurring terms, and
(b) temporal overlay showing the average publication year.
The analysis is based on the selected studies (n = 21), with a minimum threshold of two occurrences and association strength as the normalization method. Keywords were extracted from Scopus and Web of Science metadata and unified as described in Supplementary Table S5 (Source: VOSviewer v1.6.20)

The thematic map further indicates the absence of clearly developed motor themes, with several topics positioned as emerging or niche (Figure 4), suggesting that DBL development remains dependent on isolated initiatives rather than sustained research trajectories. Notably, the "teachers/teaching and learning" theme appears within the niche quadrant and is exemplified by a limited number of studies (Sivenas & Koutromanos, 2022). This positioning reflects not marginal irrelevance but a structural bottleneck, indicating that teacher preparation and pedagogical integration remain insufficiently developed within the field, a limitation further discussed in the Challenges and Success Measurement section. Taken together, these patterns directly inform RQ1 and RQ2. While current research emphasizes student engagement and activity-based learning (RQ1), it reveals limited curricular integration and insufficient development of teacher-oriented frameworks (RQ2), in line with the previously established characterization of the field. Additional keyword frequency distributions are provided in Supplementary Figure S3.

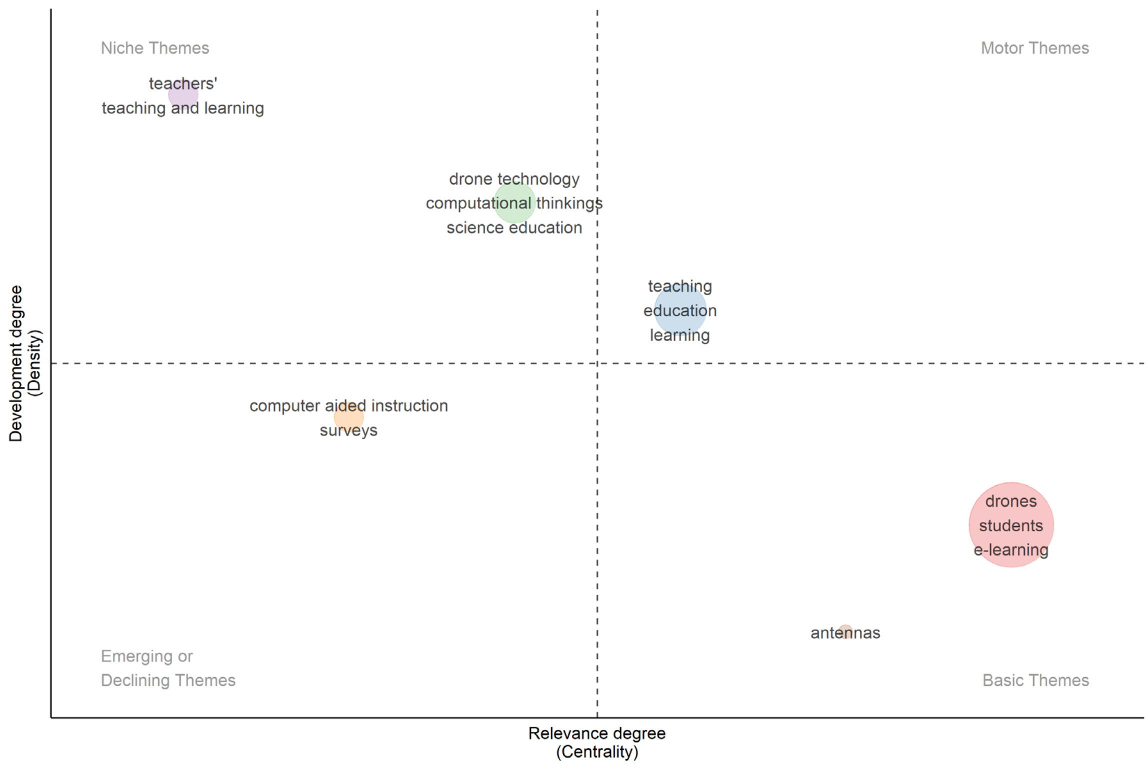


Figure 4. Thematic map of keywords, showing clusters distributed across four quadrants: Motor Themes, Niche Themes, Emerging or Declining Themes, and Basic Themes. The analysis is based on the selected studies (n = 21). Keywords were extracted from Scopus and Web of Science and unified as described in Supplementary Table S5. (Source: Bibliometrix v4.3 in RStudio 2024.09)

Geographic and authorship distribution

Research on DBL in primary education spans 12 countries, with the United States (n = 5) and Greece (n = 4) being the most represented (Figure 5). This geographic distribution suggests a limited but gradually expanding international presence, concentrated in a small number of regions.

Authorship patterns reveal low levels of international collaboration, with most studies produced within national contexts and only a small proportion involving cross-country cooperation. Existing collaborations tend to form small and weakly connected clusters, indicating limited knowledge exchange across research groups. Overall, the geographic and authorship patterns indicate concentrated contributions and limited international collaboration. Detailed author-level metrics and collaboration structures are provided in Supplementary Table S6 and Figure S4.

SYNTHESIS OF DBL IMPLEMENTATIONS IN PRIMARY EDUCATION

The reviewed studies reveal that DBL in primary education is primarily implemented through empirical and student-centered interventions, typically based on observations, surveys, and interviews. These implementations are predominantly aligned with technological and skill-based domains, particularly programming and computational thinking, while non-technological and transversal applications remain comparatively limited (Figure 6). Across the dataset, DBL is mainly used to extend or enrich existing curricula rather than to transform them. While several studies explore emerging learning domains such as problem-solving and interdisciplinarity, relatively few address broader social or contextual dimensions, such as equity, communication, or collaborative dynamics.

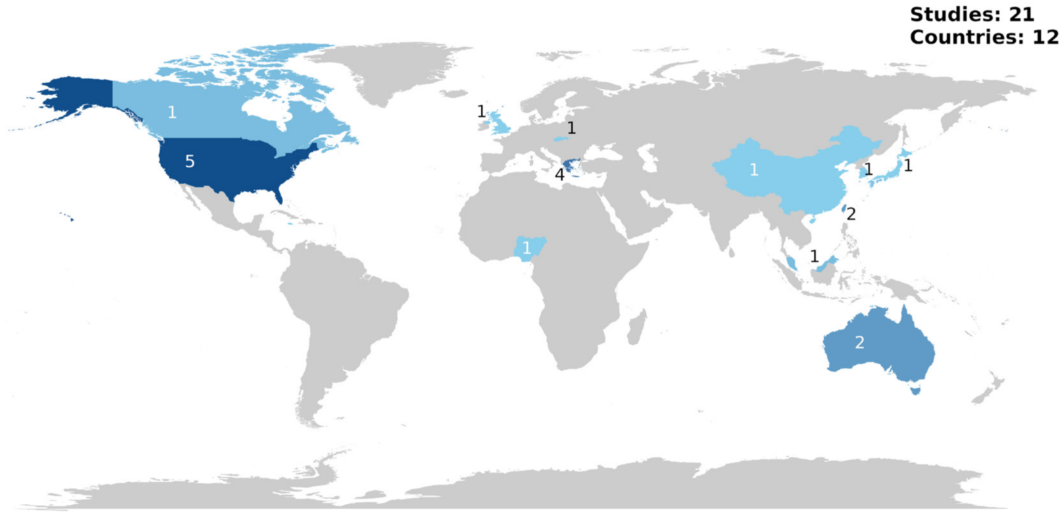


Figure 5. Geographic distribution of the included studies by country: numbers indicate the absolute count of studies per country, with a total of 12 countries represented (n = 21 studies). Data are based on author affiliations as indexed in Scopus and Web of Science. (Source: Bibliometrix v4.3 in RStudio 2024.09)

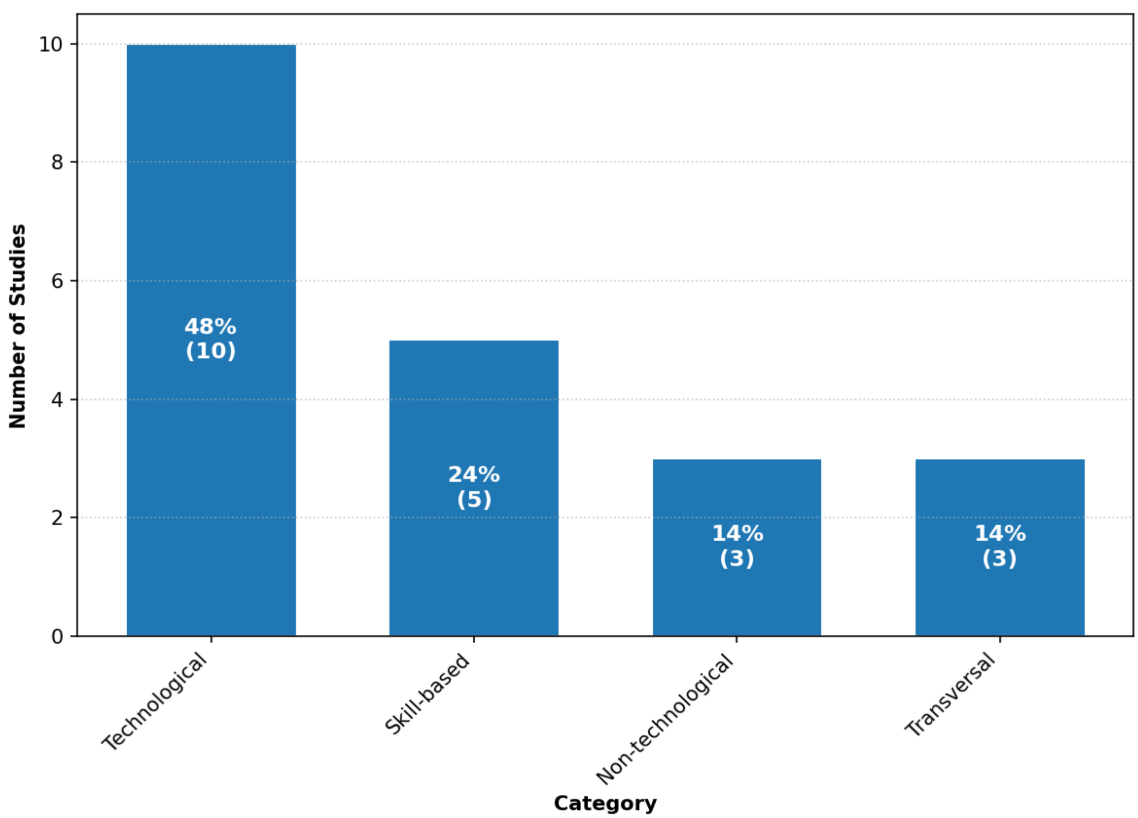


Figure 6. Distribution of studies by curricular focus (technological, skill-based, non-technological, transversal), percentages and counts are calculated based on the final dataset (n = 21)

In terms of outcomes, the evidence consistently reports gains in student engagement, motivation, and participation. However, these results are largely derived from self-reported data and short-term interventions, which limit the comparability and robustness of findings across studies.

Collectively, these competency-related findings suggest that DBL contributes not only to technological learning but also to the development of transversal competencies such as collaboration, autonomy, communication, and problem-solving. While evidence remains limited and heterogeneous, the results indicate that the educational value of DBL extends beyond disciplinary content, directly addressing RQ3.

These patterns point to a structural imbalance between reported outcomes, methods, and contexts, which is analyzed in detail in the Challenges and Success Measurement section. Detailed study characteristics and classifications are provided in Supplementary Tables S7-S8 and Figures S5-S6.

DISCUSSION

This section synthesizes the main findings of the review in relation to the three research questions: (1) the scope and educational impact of drone integration in primary education, (2) the contribution of DBL to curricular innovation and social development, and (3) its role in fostering 21st-century competencies. The discussion is structured into three parts: implementation and curricular impact, challenges and success measurement, and theoretical and practical implications.

In studies that included mixed samples (primary and secondary levels), only data explicitly referring to primary education were considered, ensuring that all conclusions remained grounded in primary-level contexts.

CURRENT IMPLEMENTATION AND CURRICULAR IMPACT OF DBL

The integration of DBL into primary education remains limited, with most efforts concentrated in STEM-oriented domains. Within the reviewed studies (n = 21), most implementations focus on technological and competency-based learning, particularly computational thinking and programming.

Research is geographically concentrated, with a small number of countries accounting for most contributions. At the same time, teachers remain underrepresented in the literature, with most studies focusing primarily on student-centered implementations. This suggests that the development of DBL has progressed without a parallel consolidation of teacher-oriented pedagogical frameworks, which may limit its scalability and long-term integration.

The evolution of DBL research indicates a gradual transition from early exploratory implementations focused on engagement and novelty toward more structured approaches that address structured models and teacher perspectives, reflecting a shift from experimentation to pedagogical consolidation. However, this consolidation remains partial and uneven across contexts. Moreover, the limited and irregular publication pattern suggests that DBL in primary education remains at an experimental stage rather than indicating marginal significance, with classroom-level implementation advancing faster than pedagogical and methodological consolidation.

A specific technological and educational convergence further explains the relevance of DBL at this particular moment. Consumer-grade UAVs capable of safe indoor operation only became widely available and affordable from approximately 2016 onward (Stephens et al., 2020), which directly explains why peer-reviewed primary education studies do not appear before 2017 (Palaigeorgiou et al., 2017; see Figure 2). Simultaneously, the growing policy emphasis on Industry 4.0 and 5.0 competencies has created an institutional demand for learning environments that develop spatial reasoning, computational thinking, and autonomous problem-solving in early education (Ilori & Ajagunna, 2020). Within this context, drones offer affordances (three-dimensional mobility, real-time data acquisition, and physical interaction with the environment), distinguishing them from other active learning technologies and positioning DBL as a timely response to a pedagogical need.

In terms of curricular impact, DBL remains predominantly implemented within STEM-related subjects, particularly programming and computational thinking. A smaller number of studies extend their application beyond STEM, including language learning, environmental education, and physical education. Beyond the general benefits of active learning discussed earlier, DBL introduces a distinctive aeronautical affordance: the ability to interact with space volumetrically through vertical mobility. This three-dimensional perspective enables forms of spatial exploration and situated observation that ground-based technologies cannot replicate, positioning drones not merely as tools for activity but as mediators of perspective. For instance, prior work has demonstrated that drones can support vocabulary acquisition through contextualized environmental experiences (Palaigeorgiou et al., 2018), suggesting that their educational value in non-STEM domains lies in their capacity to mediate immersive learning contexts rather than in direct content delivery. In this sense, drones can be conceptualized as "flying windows" (Palaigeorgiou et al., 2017), creating situated and perspective-driven learning contexts that naturally generate the need for communication, interpretation, and coordination. Through activities such as navigational tasks or search scenarios, learners engage in descriptive discourse and perspective-taking (Sivenas & Koutromanos, 2022), as well as precise verbal interaction, positioning drones not merely as observational tools but as mediators of interaction-driven learning.

Evidence consistently shows that DBL enhances student motivation, engagement, and satisfaction, particularly through hands-on and collaborative learning experiences. However, a closer examination of the reviewed studies reveals a divergence between affective and cognitive outcomes. While several studies report improvements in specific skills, such as spatial reasoning and computational thinking, most rely on self-reported perceptions rather than objective performance measures.

Importantly, although the majority of the studies ($n = 17$) involve empirical implementations (see Supplementary Table S8 for a detailed classification of implementation status), only a limited number employ pre/post comparisons or standardized assessment instruments. As a result, the evidence supporting deeper conceptual understanding and long-term learning gains remains fragmented. This imbalance suggests that current DBL implementations tend to prioritize engagement-driven outcomes, while academic impact measurement remains underdeveloped. From a practical perspective, the current evidence base does not yet provide a reliable cost-benefit assessment of DBL integration, as the reported positive outcomes are primarily engagement-driven and supported by short-term or self-reported measures. At the same time, implementing drone-based activities requires significant effort, including teacher training, technical management, safety considerations, and classroom adaptation, as educators must navigate airspace regulations and the potential for student cognitive overload (Ilori & Ajagunna, 2020; Muraina et al., 2023). This imbalance between demonstrated outcomes and implementation demands represents a critical gap in the literature, as it limits educators' and institutions' ability to justify the broader adoption of DBL.

Overall, DBL in primary education demonstrates increasing curricular relevance but remains concentrated within specific domains and implementation models. This directly addresses RQ1 by showing that, while DBL has clear potential to enhance engagement and support skill development, its educational impact remains uneven and insufficiently validated across contexts. Its broader educational potential depends on the development of teacher training, increased curricular flexibility, and the design of interdisciplinary strategies that enable meaningful integration into everyday classroom practice. At the same time, structural constraints within primary education continue to limit the adoption of innovative methodologies, restricting the expansion of DBL beyond STEM contexts. These findings are consistent with broader trends observed in complementary educational repositories, where DBL is also predominantly associated with STEM and active learning approaches.

Summarizing, regarding RQ1, current evidence indicates that DBL in primary education generates strong engagement and supports the development of transversal and technological skills, particularly within STEM-oriented contexts. Nevertheless, evidence of measurable academic impact and long-term learning outcomes remains uncertain due to the predominance of short-term interventions and non-standardized assessment methods. While DBL demonstrates clear pedagogical potential, its effectiveness in supporting sustained learning and measurable academic outcomes cannot yet be firmly established.

Challenges and Success Measurement

At this stage, it is important to distinguish between two types of limitations affecting DBL research in primary education. On the one hand, limitations at the field level stem from a small, methodologically fragmented evidence base, which restricts generalizability and the development of established pedagogical models. On the other hand, primary education constraints, including rigid curricular structures, supervision requirements, and safety considerations, directly affect the feasibility of implementation in classroom contexts.

Across the evidence base, a threefold pattern emerges: (1) outcomes are mainly reported in motivational and engagement terms rather than cognitive or long-term gains, (2) methods rely largely on self-reported and non-standardized instruments, and (3) contexts remain limited to isolated STEM-oriented implementations. This imbalance provides a framework for interpreting the methodological, pedagogical, and structural challenges discussed below.

Despite the identified positive outcomes, integrating DBL into primary education still faces substantial methodological, pedagogical, and structural challenges. Teacher preparation remains a critical bottleneck. Beyond basic technical training, educators require instructional design skills that align drone-based activities with curricular goals and meaningful assessment strategies (Hallifax et al., 2016; Isingizwe et al., 2024). Without this pedagogical support, access to technology alone does not guarantee educational impact. Evidence also indicates that brief engagements with drones rarely lead to meaningful changes in teaching practices (Goodnough et al., 2019), underscoring the need for long-term, structured professional development. This finding directly relates to RQ2, indicating that curricular innovation through DBL depends not only on technological adoption but also on teachers' pedagogical capacity to integrate these tools effectively.

Success measurement represents another weak point within the field. Although most studies involve implemented educational experiences, theoretical contributions often lack empirical validation. Moreover, the absence of standardized evaluation frameworks limits the comparability and generalization of findings. The studies use a wide range of instruments, including surveys, reflections, and observations. Rigorous comparative or longitudinal designs remain limited, with only three studies employing pre/post comparisons (Jemali et al., 2022; Palaigeorgiou et al., 2018; Tezza et al., 2020) and no longitudinal designs detected in the decade analyzed. The collaborative and creative nature of DBL also complicates the implementation of control-group methodologies, resulting in a research landscape where solid evidence of effectiveness remains difficult to establish. In consequence, reported results vary, where some studies demonstrate measurable academic gains while others emphasize benefits related to motivation and engagement.

Beyond these methodological concerns, the limited expansion of DBL must be understood through the relationship between implementation effort and perceived educational value. Integrating drone-based activities requires significant resources, including teacher training, technical maintenance, safety management, and classroom adaptation, which create substantial entry barriers within the rigid curricular frameworks of primary education.

At the student level, the operational demands of piloting may also introduce cognitive overload, particularly for younger learners, if flight mechanics compete with the intended learning objective for attentional resources (Hallifax et al., 2016; Muraina et al., 2023). This risk is not inherent to the technology but to its pedagogical design; when drone operation is appropriately guided (through simplified controls, pre-programmed flight paths, or role distribution among student groups), the focus can stay on the curricular goal instead of on technical execution, transforming accessibility constraints into design requirements rather than fundamental barriers. Importantly, drone operation in primary education contexts should not be considered a learning objective in itself, but a means to enable learning experiences aligned with the curriculum.

Looking toward future directions, the entrepreneurial and innovation dimension of DBL remains largely unexplored, possibly because innovation and entrepreneurship are not explicit curricular priorities at the primary level (Lackéus & Williams Middleton, 2015), a trend further evidenced by the peripheral positioning of these concepts in this review's keyword co-occurrence analysis (see Figure 4). Nevertheless, future initiatives could bridge this gap by incorporating project-based challenges in which students design drone-based solutions to real-world problems, connecting DBL with innovation, sustainability, and community engagement.

In summary, these findings directly address RQ2, as current evidence suggests that DBL can support curricular innovation and social development when appropriately integrated into learning activities. However, its broader adoption remains constrained by both methodological limitations and structural conditions, particularly the lack of educators' pedagogical capacity and the absence of standardized evaluation frameworks. This implies that the scalability depends less on technological availability and more on the development of pedagogically grounded integration models.

Implications and Future Research

Building on these changes, from a theoretical perspective, DBL reinforces competence-based and experiential learning models, aligning with constructivist principles (Cole et al., 1978; Piaget, 1952). By promoting knowledge construction through action, reflection, and collaboration, DBL shifts the emphasis from content transmission to the development of transferable skills such as spatial reasoning, reflective problem-solving, and autonomy, directly informing RQ3.

In practice, DBL proves to be a versatile pedagogical tool, particularly in STEM education, where drones foster computational thinking, digital literacy, and collaborative problem-solving. The evidence suggests that DBL can be especially beneficial for students who struggle under traditional instruction, enhancing engagement through embodied and project-based experiences. These considerations directly address RQ2, emphasizing the role of DBL in supporting curricular innovation and social development. Therefore, future research could focus on three complementary directions to further consolidate the field and address its current limitations.

First, longitudinal designs that move beyond isolated interventions toward sustained implementation. For instance, group-based studies spanning a full academic year, incorporating periodic drone-based activities aligned with curricular objectives (e.g., environmental monitoring or spatial mapping tasks), would allow researchers to distinguish between novelty effects and sustained competency development in areas such as computational thinking and spatial reasoning. The inclusion of repeated measures across multiple time points, supported by more standardized evaluation frameworks that combine performance-based and reflective indicators, would provide more robust, comparable evidence than currently available.

Second, comparative designs that isolate the specific contribution of aerial affordances. Future studies could compare drone-based activities with functionally equivalent tasks using other technologies rather than contrasting DBL exclusively with traditional learning. Examples include ground-based robotics platforms for programming-related learning, or passive geospatial tools such as Google Earth for spatial and language-related tasks (Hodgson & Piovan, 2022). Such comparisons would help determine whether observed outcomes derive from active learning approaches in general or from the distinctive characteristics of UAVs, such as three-dimensional mobility and real-time environmental interaction.

Third, the development of structured non-STEM implementations with clearly defined communicative and creative objectives. Task-based scenarios, such as coordinated navigation or search-and-rescue activities, require students to produce precise verbal instructions, negotiate shared understanding, and adapt language use in real time. Systematizing the analysis of speech, interaction patterns, and task performance in such contexts would pave the way for replicable pedagogical models.

Finally, regarding RQ3, current findings indicate that DBL can foster competencies such as autonomy, collaboration, and context-based problem-solving through experiential and interaction-driven learning environments. However, the extent to which these competencies are sustained and transferable remains unclear due to the lack of longitudinal and comparative designs. This implies that competency development in DBL is not inherent to the technology itself, but depends on its pedagogical orchestration and alignment with instructional design and assessment practices.

CONCLUSIONS

This systematic review positions DBL in primary education as a promising yet still maturing pedagogical domain, characterized by strong engagement-driven outcomes but limited methodological maturity.

Across the reviewed studies, evidence consistently supports DBL's capacity to enhance motivation, collaboration, and participation, particularly within STEM-oriented contexts. However, the current evidence base remains constrained by short-term interventions, heterogeneous methodologies, and a predominance of self-reported measures, limiting the ability to draw robust conclusions about long-term academic impact.

The findings suggest that the educational value of DBL does not reside in the technology itself, but in its capacity to enable experiential, situated, and interaction-driven learning environments. In this sense, DBL represents less a technological innovation and more a pedagogical opportunity, whose effectiveness depends on coherent instructional design, teacher readiness, curricular alignment, and evidence-based integration. While ongoing technological advances, such as autonomous navigation, miniaturization, and AI-enhanced capabilities (Qin et al., 2023; Stephens et al., 2020), are likely to expand the versatility and accessibility of drone-based applications, significant evidence gaps remain, particularly regarding non-STEM contexts, diverse learning environments, long-term outcomes, and standardized evaluation models.

Beyond synthesizing existing evidence, this review offers a stage-specific, analytically grounded perspective on DBL in primary education. By combining bibliometric mapping with pedagogical interpretation, distinguishing between field-level and contextual constraints, and conceptualizing the unique affordances of UAVs, the study provides a structured basis for future research and instructional design. This positions DBL not as a fully consolidated educational approach, but rather as an evolving field whose future development will depend on integrating pedagogical frameworks, standardized evaluation methods, and sustained implementation models.

LIMITATIONS OF THE CURRENT RESEARCH

While this review provides valuable insights into the integration of DBL in primary education, it also presents limitations. Restricting the analysis to English-language, peer-reviewed publications indexed in Scopus and Web of Science may have excluded studies published in other languages, particularly in regions where primary education research is often disseminated in languages such as Spanish, Mandarin, Portuguese, or local languages. Likewise, conference proceedings, practitioner reports, or pilot projects are published in local journals. As a result, this reliance on formal databases may bias the synthesis toward high-impact academic publications, potentially overlooking grassroots or context-specific initiatives that could offer valuable perspectives for DBL integration in diverse educational settings. Additionally, some records may not be retrieved or fully represented due to incomplete metadata (e.g., absence of indexed keywords), particularly in conference proceedings, which may affect both search retrieval and subsequent bibliometric analyses.

Some included studies involved mixed samples of primary and secondary education; in such cases, only data explicitly referring to primary classrooms were extracted and analyzed to maintain alignment with the review's scope. Although this decision supports methodological consistency, it also narrows the interpretive context of some findings. The limited number of eligible studies reflects the scarcity of empirical research on DBL in primary education rather than a limitation of the search process. Similar trends are reported in recent reviews: M. Y.-C. Jiang et al. (2024) identified only a modest number of relevant studies across all educational levels, and Yeung et al. (2024) reported a comparable trend in secondary education. These converging findings confirm that small samples are characteristic of this emerging research area. While this limits the generalizability of results, it underscores the need for broader, longitudinal investigations as the field evolves.

A further limitation relates to the use of citation-based metrics. Citation counts are influenced by factors such as publication age, self-citation practices, journal prestige, and language of publication. These biases may affect the apparent impact of studies, so citation indicators should be interpreted with caution and not taken as direct measures of research quality (Aria & Cuccurullo, 2017).

Data Availability Statement

The following supporting materials are openly available at Zenodo: https://doi.org/10.5281/zenodo.17038756

The final dataset of the 21 included studies in CSV format; supplementary Tables S1-S8 in markdown and PDF formats; R and Python scripts; and Figures 1-6, S1-S6 in PNG format.

Dedup script available on request.

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Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Considerations

This study is a systematic review of published research and does not involve human participants. Therefore, ethical approval was not required. All included studies were assumed to have undergone ethical review in accordance with their respective institutional and national guidelines.

Use of Artificial Intelligence

The authors used OpenAI ChatGPT exclusively for linguistic editing and style refinement of the English text. No AI tool was used for content generation, analysis, or interpretation.

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