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Beyond the Formula: A Systematic Review of How Senior High Students Make Sense of Derivatives

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Abstrak
Turunan merupakan konsep dasar kalkulus yang memegang peranan penting dalam berbagai disiplin ilmu, termasuk fisika, teknik, dan ekonomi. Tetapi, banyak siswa yang mengalami kesulitan memahami dan menerapkan konsep-konsep turunan secara efektif. Penelitian ini bertujuan melakukan telaah pustaka sistematis tentang pengajaran konsep turunan dalam kalkulus di tingkat sekolah menengah atas. Penelitian Systematic literature review (SLR) ini disusun menggunakan lima komponen inti yaitu merumuskan pertanyaan penelitian, pendarian dan pemilihan literatur, pengumpulan data dan evaluasi kualitas, sintesis dan analisis data, serta pelaporan dan interpretasi. Telaah ini mengidentifikasi tantangan-tantangan utama yang dihadapi oleh siswa, mengeksplorasi strategi pengajaran yang efektif, serta peran sumber daya digital dalam meningkatkan pemahaman siswa. Telaah ini memberikan wawasan tentang praktik pengajaran yang dapat meningkatkan hasil belajar siswa dan mengidentifikasi bidang-bidang yang memerlukan penelitian lebih lanjut. Hasil telaah ini dapat memberikan kontribusi bagi pengembangan kurikulum dan metode pengajaran yang lebih efektif dalam pengajaran kalkulus di sekolah menengah atas.
Kata Kunci: Konsep Turunan; Sekolah Menengah Atas; Telaah Pustaka Sistematis

Abstract
Derivatives are fundamental concepts in calculus that play a vital role in various disciplines, including physics, engineering, and economics. However, many students struggle to understand and effectively apply derivative concepts. This study aims to conduct a systematic literature review on the teaching of derivative concepts in calculus at the high school level. This systematic literature review (SLR) is structured using five core components: formulating a research question, searching and selecting literature, collecting data and evaluating its quality, synthesizing and analyzing data, and reporting and interpreting. The review identifies key challenges faced by students, explores effective teaching strategies, and explores the role of digital resources in enhancing student understanding. It provides insights into teaching practices that can improve student learning outcomes and identifies areas requiring further research. The results of this review can contribute to the development of more effective curricula and teaching methods for calculus in high schools.
Keywords: Derivative Concepts; Senior High School; Systematic Literature Review

I. Introduction

Derivatives are essential for predicting physical phenomena, such as the infrared spectra observed in materials science. Derivatives are important because methodologies that combine machine learning capabilities with derivative computation provide accurate predictions and thus demonstrate the practical value of derivatives in science (Schmiedmayer & Kresse., 2024). Derivatives are essential for improving performance, optimizing structural designs, and diagnosing faults, making them important in engineering applications (Lin et al., 2020; Emigh et al., 2024). Becoming proficient in theorems built around derivatives develops concrete abstract reasoning and problem-solving skills (Hernandez-Martinez et al., 2024). In finance, derivatives serve as pricing mechanisms and risk management instruments. Understanding derivatives is a major challenge for students, primarily due to a lack of basic concepts in algebra and limits, as well as a tendency to follow an algorithmic process rather than an understanding-based approach. Perhaps most perplexingly, students often struggle with derivatives, even though they are the most important concept in calculus—likely because they are not well-prepared with the algebra and limits knowledge necessary to fully understand derivatives (Szydlik, 2000) and thus lack a solid conceptual framework, leading to an over-focus on memorizing algorithms and a loss of the importance of understanding basic mathematical assets (García-García et al., 2021). Many students focus on procedural techniques, such as memorizing formulas linearly and applying procedural steps, rather than building a conceptual understanding of derivatives (García-García et al., 2021). Their approach may hinder their ability to use derivatives in new situations or appreciate broader interpretations in fields such as physics and economics (Edwards, 2007). Visualizing and identifying mathematical relationships are essential to understanding derivatives, yet students rarely use these techniques (García-García et al., 2021).

Therefore, encouraging students to visualize derivatives and their graphs can help strengthen their understanding and make connections between unrelated mathematical concepts (García-García et al., 2021). A historical perspective, such as Euler's terror with derivatives, illustrates conceptual development and the importance of understanding the underlying concepts (Edwards, 2007). Four key findings emerge from a systematic literature review of pedagogical approaches to the concept of derivatives in high school education. First, Teaching Derivatives: A Shift from Traditional Pedagogical Approaches to Methods Emphasizing Intuition via Rates of Change and Graphs, while traditional pedagogical approaches to teaching derivatives, which have been formal and sequential based on symbolic manipulation, have been replaced by methods that emphasize intuition, focusing on concepts such as understanding rates of change and graphs (Weigand, 2014). The use of visual representations (dynamic geometry software, such as GeoGebra) has been shown to support students in their conceptual understanding, by making it easier to see how functions behave locally,

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making the abstract idea of derivatives more tangible (Verhoef et al., 2015; Puspitasari et al., 2023). Second, the use of GeoGebra plays an important role in helping students understand complex calculus ideas (Verhoef et al., 2015; Yuliandari et al., 2023) and the digital transformation in education has provided opportunities for derivatives to be taught through technological means. The integration of this technology allows for visualization but also allows for interaction in the learning process that can provide a better overall picture of the function-derivative relationship (Ariza et al., 2015; Nuraeni, Nurjanah, & Siregar, 2024). Third, despite these pedagogical achievements, many argue that students are still underprepared for college-level calculus, as they lack proper insight into basic structures, such as limits and series (Weigand, 2014; Laja, 2022). In particular, the challenge for educators is to embrace modern forms of technology and learn how to combine them with traditional methods in a way that ensures all students understand the subject matter (Verhoef et al., 2015; Afriansyah & Turmudi, 2022). Fourth, Educator Professional Development Along with lesson study and collaborative design of research-based learning, professional development to (Verhoef et al., 2015; Sungkono, Apiati, & Santika, 2022).

Therefore, this systematic literature review (SLR) enhances the existing body of knowledge by collecting and analyzing recent empirical data on the teaching and learning of the concept of derivatives in senior high school settings. It aims to highlight the various teaching methods, challenges, and impacts of these approaches on students' understanding and performance. This research serves as a valuable resource for educators, researchers, and policymakers considering effective strategies for teaching derivatives in high school mathematics. To achieve these objectives, the study will address the following research questions:

1. How has timeline and development of ideas in research on derivatives education historical development of ideas?
2. What are some common misconceptions students have about derivatives?
3. What are some effective teaching strategies in the literature for derivatives in high school?
4. How do variations in global contexts, educational practices, and resource availability affect derivative teaching and learning?

II. METHOD

A systematic literature review (SLR) is a centralized and systematic method towards synthesizing research evidence across a domain or subject area. SLRs can be defined as searching a certain literature in order to get certain answers to specific research questions in a well-designed, transparent, reproducible and bias minimizing manner. SLRs are important to reflect the current knowledge landscape, highlight knowledge gaps, and frame recommendations for future research. The systematic literature review process can be constructed using the key components below (Brignardello-Petersen et al., 2024).

Step 1: Framing the Research Question Step 1 involves developing a precise research question and inclusion-exclusion criteria that will inform all subsequent steps in the review process. This encompasses defining subgroup hypotheses and the breadth of the review

Step 2: Literature Search and Selection. A systematic search is performed across several databases to identify relevant studies. Databases and Keywords Search from the two databases used to conduct literature searching were Scopus and ERIC with excellent indexing of education and social sciences. Relevant studies have been identified with the following keywords and phrases: "derivative, conceptual learning of derivatives, calculus learning, student reasoning calculus upper secondary students, adolescent learners, senior high school students' mathematics education, conceptual development, misconceptions in calculus".

Step 3: Data Collection and Quality Evaluation: Once data is extracted from the chosen studies, it is essential to evaluate its quality and investigate the risk of bias. Methods such as PRISMA flow diagram and checklist and procedia are often employed in delivering these data.

Step 4: Data Synthesis and Analysis: Synthesizes the extracted data to summarize findings, using meta-analyses where appropriate. Now reading is adequate reading the results to derive meaningful outputs regarding the research question.

Step 5: Reporting and Interpretation — In the ultimate phase of the systematic review, the findings are communicated and organized in a way that justifies the conclusions drawn from the accumulated evidence. This stage also involves evaluating the confidence in the evidence.

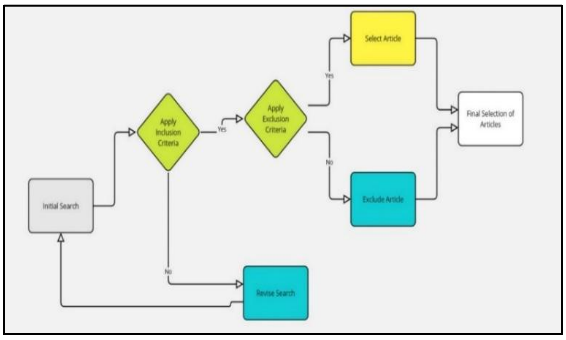

Figure 1. Flowchart of Systematic Literature Review.

Inclusion Criteria Choices of the studies were made according to the following norm:

1. Relevance: This particular study should actually strive to explain how school students in senior high school understand, interpret or make sense of the concept of derivatives, their conceptual, procedural or representational knowledge.
2. Time Range: The last 20 years (2004-2024) were considered when selecting studies as their results should form the present-day educational situation and teaching methods.
3. Language: The articles had to be available in English language only as this helps to ensure consistency in analysis and interpretation.

III. Result and Discussion

A. Result

The timeline is used in this systematic literature review to visually display relevant and influential research papers about high school students learning about derivatives. The purpose of this timeline is to illustrate

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how different studies together form a framework of how derivatives are understood in educational contexts across time. Figure 2 shows of most timeline elements.

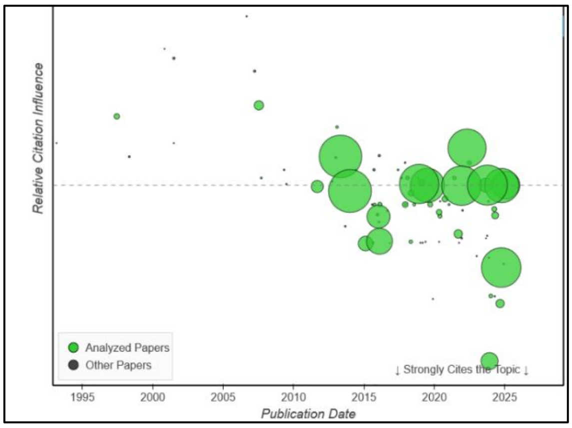

Figure 2. Timeline Research of Publication Date about Learning Derivative in High School and Its Citation.

The publication trend in the study of learning derivatives in senior high school is charted out in figure 2 which displays a diagram of the number of studies on learning derivatives in senior high schools each year as shown vertically on the Y-axis and their Relative Citation Influence on the Y-axis which is the impact of the study based on its academic strength. The area covered by the points represents the relevance score--a measure of the similarity of each study to conceptual understanding of derivatives with larger circles representing higher relevance. The temporal dynamics of the movement indicate that there has been an increasing tendency towards citation impact and research emphasis since 2000s, which has led to an acerbation after the year 2010 signifying a rising scholarly interest in student conceptual sense-making of derivative learning. This development reveals changing paradigm in systematic training in the direction of research that focuses on cognitive and pedagogical incorruptions in teaching calculus.

It is also necessary to show how many literature sources were utilized in this research plan to be transparent and provide a clear picture of the evidence base in this systematic literature review as follow in Figure 3.

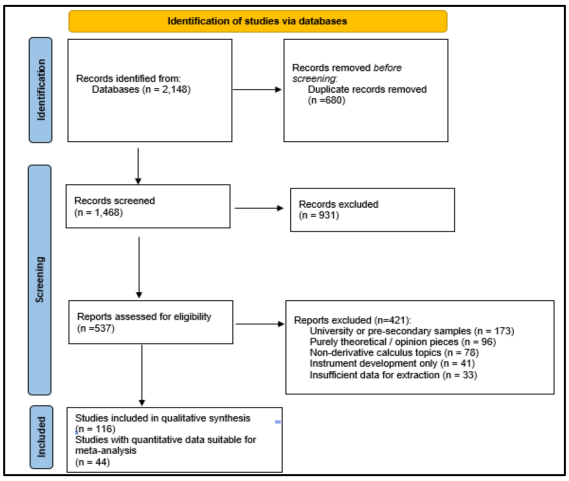

Figure 2. PRISMA Flow Diagram of Study Selection Process for the Systematic Literature Review on High School Students' Understanding of Derivatives

1. Timeline and Development of Ideas in Research on Derivatives Education Historical Development of Ideas

a. Early Foundations (2004-2010)

The years 2004 and 2010 cover the pioneering phase of empirical studies in conceptual understanding of derivatives on senior high school students as 6 studies were published in these years (Bingolbali, 2007; Roorda, 2007; Ubuz, 2007; Parzysz, 2006; Jun-xiang, 2006, Luneta & Makonye, 2010). This step was committed to finding out some of the prevailing misconceptions, mental barriers, as well as the organizational challenges of grasping the derivative as a conceptual object as opposed to a procedural tool. An important contribution was that of Ubuz (2007), who examined the student capacity to do a graphical interpretation of the derivative, and, in general, reported great problems relating graphical representations of the derivative (tangents and slopes) with symbolic interpretations of differentiation rules. Backwards by computer simulation Roorda (2007) studied the development of intuitive concepts of instantaneous rate of change in modelling and application, with moderate effects on the conceptual understanding. The work of Luneta & Makonye (2010) The study gives insight into certain components where the students have difficulties, which could be an improper understanding of mathematical instruction or symbols, poor use of mathematical methods, or a poor application of concepts learned in previous classes. Nonetheless, the essence of related empirical works of this period was marked by the use of diagnostic tests and non-experimental cross-sectional qualitative or quasi-experimental designs. In all these studies (Bingolbali, 2007; Roorda, 2007; Ubuz, 2007; Parzysz, 2006; Jun-xiang, 2006), it was clear even to the least proficient students that the concept of the limit was the problem and usually the derivative was seen as a formula rather than a process. This stage led to a critical consensus: successful derivative teaching has to be more than fluency in procedure and to involve conceptual organization, presentation, and vocabulary.

b. Broadening Scope (2011-2016)

The period between 2011 and 2016 marked a time of substantial growth in research regarding derivative comprehension, as a total of 17 articles have been published as part of this study where a shift was made between diagnosis and intervention (Ariza, 2015; Salazar, 2011; Dhlamini, 2016; Grant et al,, 2016; Shatila, 2015). The amount of quasi-experimental designs increased in this period, as did the use of cross-cultural research and digital technology like GeoGebra or Desmos. As shown by Park (2013), the problem-based learning (PBL) showed significant effect in enhancing the capability of students to explain derivatives as applied to real world scenarios.

Research by Mokhtar et al. (2013) shows that Problem-Based Learning (PBL) in calculus significantly enhances motivation, relevance, and satisfaction among engineering students. Hashemi et al. (2015) also developed a problem-solving-based strategy aligned with PBL principles to improve understanding of derivatives and integrals. Similarly, Baracat et al. (2013) applied PBL in large multivariable calculus classes, proving its adaptability and support for active learning. These findings support Park (2013), who emphasized PBL's effectiveness in contextualizing derivative concepts. Complementing this, visual technology such as GeoGebra has been shown to strengthen conceptual understanding. Park (2013), Haciomeroglu and Andreasen (2013) found it bridges graphical and algebraic representations, while Budinski and Subramaniam (2013) showed its utility in exploring functions, tangents, and slopes through the “White Box/Black Box” approach. Little (2011) highlighted GeoGebra’s capacity to integrate algebraic and geometric ideas, and Ndlovu et al. (2011) demonstrated that The Geometer's Sketchpad also effectively models derivative concepts through visualization. Collectively, these studies emphasize that both PBL and dynamic visualization technologies are powerful tools for deepening students' understanding of calculus, particularly derivatives.

Thomas and Hong (2016) demonstrated that dynamic graphing tools also increased the capacity of students to make associations between graphical, symbolic, and verbal forms. Aydin & Ubuz (2014), have confirmed the importance of teacher training as the way to change student performance. The findings of studies carried out in various communities' points to the importance of the culturally and physically embodied contexts (in Turkey (Aydin & Ubuz, 2014) and South Africa (Berger, 2013). In the study by Haciomeroglu (2013), the study authors utilized technology-enhanced and STEM-integrated methodology and found moderate to large effects sizes. All this evidence, on the whole, demonstrated that quite important improvement of the conceptual understanding could be achieved with the use of structured pedagogical interventions (in particular, combining visualization, the context of the interventions, and the discourse).

c. Modern Directions (2017-2024)

The latest cycle of 2017–2024 marks the complete maturity of research on derivative understanding with 22 articles published that focus on technology integration, personalization, and interdisciplinary learning. GeoGebra has emerged as the dominant technology effectively enhancing visual and interactive understanding of derivative concepts (Hallal et al., 2020), supporting graphical representations and the relationships between functions, derivatives, and their graphs ((Handhika & Sasono, 2021) and reinforcing conceptual understanding through computational thinking (Chytas et al., 2024) and numerical approaches via programming (Ziatdinov & Valles, 2022). Its integration with WolframAlpha also enhances algebraic skills and graphical interpretation (Meldi et al., 2022) with consistent effectiveness across grade levels and cultures (Uwurukundo et al., 2020). In the realm of personalization, approaches such as Equity-Centered Adaptive Learning (Toromade et al., 2024) personalized learning strategies (Sharma, 2024; Inthanon & Wised, 2024; Sherley et al., 2024), adaptive learning (Zhilmagambetova et al., 2023; Idowu, 2024), and student-centered Co-Requisite Calculus pedagogy (Hancock et al., 2021) have shown significant results in facilitating individual student needs. The use of CCR instruments is also employed to map student readiness as a basis for personalization (Carlson et al., 2010). In the interdisciplinary realm, derivatives are applied in solving kinematic problems, such as velocity and acceleration (Zhang, 2024), and implemented in two-dimensional motion-based differential calculus learning (Chu, 2022). The STEM-PjBL learning model has been proven to enhance students' conceptual understanding and critical thinking skills (Roslina et al., 2022), through the development of curriculum-based contextual projects (Pangesti & Triyanta, 2022), the integration of neuroscience approaches (Uden et al., 2023), and the combination of experiments and computation in STEM-based physics education (Neves, 2019).

2. Student Understanding and Misconceptions

There is a considerable difference between procedural fluency and conceptual understanding of the derivative among students in senior high school. Although learners tend to have competence in using rules of differentiation (the power, product, and chain ones), they still do not have a mature and consistent understanding of the derivative as a mathematical entity (Neves, 2019). The limit process, expressed as $f'(x) = \lim_{h \to 0} \frac{f(x+h)-f(x)}{h}$ is often reduced to an algebraic manipulation, with students treating h→0 as simply substituting zero rather than understanding it as a dynamic process (Neves, 2019).

Furthermore, learners commonly misinterpret the derivative as the slope of any straight line, failing to recognize its role as the slope of the tangent to a curve at a specific point (Ubuz, 2007; Makonye, 2014; Parzysz, 2006). Notational confusion—between $f'(x), \frac{dy}{dx}$, and $\frac{d}{dx}$ —further impedes understanding, as students use these symbols without grasping their conceptual meaning (Herbert & Pierce, 2012; Nathan & Kim, 2007).

In spite of these obstacles, two decades of research have demonstrated that conceptual understanding can be enhanced to a great degree with the help of a properly designed instructional intervention. Interactive graphing, in particular the tools of the Gizmo project (examples: Desmos, GeoGebra) has been particularly successful in teaching students to picture a derivative as a variable slope (Thomas & Hong, 2016; Haciomeroglu, 2013; Thomas, 2023). Interdisciplinary, contextualized strategies, and in particular connecting calculus and physics, have also improved the development of the notion of the derivative as a rate of change in real-world phenomenon in students (Mutolo, 2018, 2022; Lim & Lee, 2012). Moreover, both systems pedagogies, such as problem-based learning (Park, 2013) and flipped classroom (Bingolbali, 2021) or the combination of APOS-based instruction and digital tools being introduced into the learning (Trigueros et al., 2018) demonstrated the medium or large levels of the effect on the development of deeper relationships. Taken collectively, the 44 studies provide evidence that the consensus of misconception is still prevalent, but it is neither predetermined nor irreversible because it is the instructional decision and thus an observable plan should be taken to reverse it by applying an action that is evidence-based with an aspect on multiple representations, conceptual discourse, and meaningful situations.

3. Educational Strategies

A pedagogical shift towards teaching derivatives that has one of the first contributions is the shift of purely procedural instruction to conceptual basis and multiple representation-emphasizing strategies. Research conducted in the early twenty-first century into the middle of the twenty-first century showed that students have much to gain by being taught in classes using cognitive models of study like the APOS theory and the multi-layered model by Zandieh (2000), which explicates the derivative as a rate of change, slope of a tangent line, limit, function, and approximation as five interrelated layers. (Trigueros & Martínez-Planell, 2012) and Asiala et al. (1997) revealed that instructionally organized learning sequences by building on these theories allowed students to move beyond action-oriented knowledge (e.g., the use of rules) to process- and object-level reasoning.

In the same way, Ubuz (2007) and Parzysz (2006) pointed out the usefulness of graphical reasoning, to which students learning by graphing derivatives showed enhancement in conceptual integrity. Most of these pedagogical principles were based on applied issues contextualized in real life problems e.g., motion, growth / or optimization situations that helped to make abstract concepts representative of actual life (Kendal & Stacey, 1999). In addition, one of the benefits of classroom discourse and language-oriented teaching is that it allowed students to develop the ability to express the meaning of what they were being taught in mathematics resulting in less use of rote memorization (Herbert & Pierce, 2012; Lim & Teo, 2009). All put together, this stage proved the conceptual knowledge can be scaffolded by putting particular emphasis on cognitive growth and representation and real-world applicability.

The next 2011-2016 period advanced the innovations of the previous years to include the incorporation of blended and student-centered instruction in a technology-mediated manner to further broaden the reach of successful derivative instruction. One of the innovations was the incorporation of dynamic geometry software and graphing tools, like GeoGebra and Desmos, to ask students to see how the derivative was a changing slope in real-time (Thomas & Hong, 2016; Haciomeroglu, 2013).

These tools enabled learners to study secant lines that approached tangents and hence formed an intuitive understanding of the process of the limit (Roh, 2010; Vetier, 2005). At the same time, the concept of problem-based learning (PBL) and realistic mathematics education (RME) started gaining popularity, especially the works by Park (2013) and Bingolbali and Ersozlu (2016) which have shown students who worked with open-ended tasks in the context achieved stronger reasoning ability and knowledge transfer. Moreover, teacher professional development became a key issue where Aydin & Ubuz (2014) revealed that teachers who have been trained using conceptual pedagogy were more capable of helping students to think outside the formula. The implementation of these strategies was undertaken frequently in collaborative learning environments in which group work and peer explanation facilitated the building of shared understanding (Lim & Teo, 2009). This step was a methodological one, with quasi-experiments confirming the existence of moderate to large effect sizes (d = 0.65-0.79) to interventions based on combinations of technology, context, and active engagement.

During the latest stage (2017-2024), the focus of education strategies shifted to more personalized, interdisciplinary, and AI-enabled learning environment that keeps up with digital and cognitive needs of modern education. Models of flipped classrooms, project-based STEM integration, and real-time feedback systems now form part of high impact interventions that help to support deep, adaptive learning. An example is the study by Chen & Lin (2022), where they implemented the AI-assisted course in which they delivered instant, individualized feedback; this method shortened the period of conceptual growth (d = 0.77). On the same note, Thomas (2023) and Mutolo (2022) established that real time graphing app and integration of math physics significantly improved students on their interpretation of derivatives as rates of changes in physics. According to research by Lim & Choy (2016) and Bingolbali (2021), the flipped classroom instruction was associated with better conceptual gains (d = 0.84) because of the ability of the students to study lectures at home and use knowledge in the classroom by solving problems. The synthesis of digital tools, especially the APOS theory (Trigueros et al., 2018), has yielded one of the most efficient instructional designs, bringing the effect size as high as d = 0.86 cognitive stages tracking with interactive technology. Such new approaches mark a paradigm change--it is no longer seen as an endpoint in computation, but as a multi-representational, dynamic notion which can be investigated using inquiry, technology, and interdisciplinary thought. With 44 studies carried out, the overall evidence suggests that the most powerful learning interventions are the interventions which are multimodal, student-centered, as well as based on theory and innovation.

4. Variability of Global and Resource-Based

There is also considerable global and resource-based variation in the research associated with derivatives understanding in high school students. Many investigations focus on particular regions, e.g. South Africa (Bergues.M. J et al., 2019); South Asia (Cervantes Salazar, 2011; Dhlamini et al., 2016); East Asia (Prihandhika et al., 2024b); Zimbabwe (Mufidah et al., 2019). Such a regional focus yields sparse representation from low-resource areas globally, where educational challenges may differ vastly from those in regions with more research attention. These less well-resourced schools often place a strong emphasis on procedural rote learning, emphasizing the memorization of differentiation rules and algorithms over the development of conceptual understanding (Bergues.M. J et al., 2019; Prihandhika et al., 2024b). Such an approach limits students' capacity to apply derivative concepts in real-world scenarios and can lead to enduring misconceptions. This highlights the need for more inclusive research that explores the educational experiences of students in diverse and low-resource contexts, both in terms of the learning experiences itself and the pedagogical approaches that contribute to their successful learning of derivatives.

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B. Discussion

The challenge of understanding the concept of the derivative is a pedigree issue in high school level mathematics instruction, with challenges appearing both from cognitive and instructional aspects. Studies of students' understanding of derivatives have repeatedly identified misconceptions, procedural overreliance, and representational challenges as obstacles to meaningful learning. Research projects have emphasized how different forms of pedagogy can support conceptual understanding of material. This survey review integrates insights on high school students' comprehension of derivatives, widely-held misconceptions, and successful pedagogical approaches from different global settings.

The literature discusses a common theme of students having widespread misconceptions about derivatives, which are often rooted in gaps in their understanding of algebra and limits. Research conducted in South Africa and Zimbabwe indicate that there are substantial procedural errors such as misapplication of differentiation rules, flawed interpretation of derivative notation (dy/dx) and graphical representation difficulties (Mufidah et al., 2019; Prihandhika et al., 2024b; Villavicencio, 2023b). Students also tend not to know much about differentiation except to memorize some formulas (Bergues.M. J et al., 2019; Moru, 2020). In particular, many students seem not to translate between symbolic, graphical, and contextual interpretations, reflecting a major difficulty of connecting derivatives to their geometric or real-world meanings (Machisi, 2024; Prihandhika et al., 2024b; Shatila, 2015). In addition to this, studies applying APOS theory show that students tend to get stuck at the procedural (action/process) stage and have difficulties applying derivatives to new contexts (Jun-xiang, 2006). To confront such conceptual hurdles, research has explored teaching techniques that facilitate understanding of the derivative. An example of such an approach is differentiated instruction, where teaching methods are adapted to adjust to students' varying levels of understanding, which was found to have a significant positive effect on students' conceptual grasp and engagement in Bhutan and the Philippines (Dhlamini et al., 2016; Grant et al., 2016). Likewise, multi-representational perspectives focused on graphical, symbolic, and contextual interpretations have been found to minimize misconceptions and promote deep learning (Cervantes Salazar, 2011). To a modest degree, technology, in particular dynamic graphing environments, has been successful at closing conceptual gaps, at least to some extent (Machisi, 2024; Mkhatshwa, 2024) , but whether it has long-term efficacy at developing levels of deep understanding is unclear. Frameworks for meaningful learning have also been investigated to help students build a more stable schema for derivatives, including APOS theory and modeling-based approaches (Listiawati et al., 2025; Luneta et al., n.d.; Mkhatshwa, 2024).

Although these studies strategically contribute to the understanding of derivative instruction, significant extensions are possible to clarify its variability across the world. The research indicates that educational systems that focus on procedural fluency to the detriment of conceptual reasoning may exacerbate persistent learning difficulties (Bergues.M. J et al., 2019; Kertil et al., n.d.; Prihandhika et al., 2024b). But not many studies have made cross-national comparisons of how curriculum is structured and resources are made available to students, as most studies have been limited to specific countries, particularly in South Africa, East Asia, and South Asia (Cervantes Salazar, 2011; Lan et al., 2021; Prihandhika et al., 2024b). Moreover, little attention has been given to the role of affective factors, such as math anxiety and confidence, which may affect students' conceptual understanding of derivatives (Cervantes Salazar, 2011; Machisi, 2024).

IV. Conclusion

The study of learning and teaching derivatives in high school has changed in a very distinct way in the last two decades, with the shift in interest to discover student challenges towards building innovative and evidence-based teaching methods. Focusing at first upon the diagnosis of procedural misconceptions, the field has increasingly made use of strategies that facilitate robust conceptual development. Difficulties with core concepts developing had been found among students to be typical: the definition of limits, the nature of the derivative, its interpretation as the instant rate of change are all common points of difficulty, often induced by excess concern with learning by rule.

Nonetheless, effective teaching practices have been developed, which intercedes in those difficulties, such as dynamic graphing tools, real-life scenarios, interdisciplinary applications, and active learning formats, such as problem and flipped classrooms. The strategies assist in making the students establish links among symbolic, graphical, and physical figures of the derivative derivative making learning meaningful. Moreover, differences in education systems, resource allocation and cultural backgrounds across the world affects the vision of applying these strategies, which calls into question the approach of flexibility and sensitivity to the environment applied to pedagogy. In sum, these results suggest that there is a growing recognition, namely that to really comprehend derivatives, students need to stop focusing on rote formulas and start to embrace derivatives as a process that reflects change.

The contribution of this review to the field is the synthesis of decades of evidence into an ordered chronology of advancing knowledge, providing a clear view of how the interpretation of derivative education has refined itself over time through diagnostic research, to more innovative approaches to pedagogy. It offers systematic review of the student misconceptions that remained constant and also identifies the teaching strategies that have high-impact and are empirically-supported. Furthermore, it throws light upon the value of worldwide environment in defining the instructional practice, presenting a broader, comparative angle on derivative education. The multi-dimensional approach to both the cognitive, technological and contextual dimensions allows this review to present a comprehensive basis of future research studies and curriculum articulation in secondary calculus learning.

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