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Errors in solving quadratic equations and their impact on secondary school students' mathematics performance: A case study in Lebowakgomo sub-district

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ABSTRACT

Errors in solving quadratic equations are common among high school students and can significantly impact their mathematical proficiency. This study aimed to investigate the types of errors made by Grade 10 students and identify the factors contributing to these errors. The study was conducted in three senior secondary schools in Lebowakgomo District, Limpopo Province, involving ninety-nine Mathematics students, with nine selected for interviews. Data were analyzed quantitatively through students' test scores and qualitatively using document analysis and interviews. The findings revealed that students' difficulties were often reflected in errors related to carelessness, misapplication of numerical operations, order of operations, and challenges in handling algebraic equations. These conceptual and procedural inconsistencies hinder students' problem-solving abilities. The implication of this study is the urgent need for targeted instructional strategies that address conceptual understanding and procedural fluency to improve students' academic performance in Mathematics.

Kesalahan dalam menyelesaikan persamaan kuadrat dan dampaknya terhadap performa matematika siswa sekolah menengah: Studi kasus di sub-distrik Lebowakgomo

Kata Kunci:

kesalahan, kesulitan belajar, performa matematika, operasi numerik, persamaan kuadrat

ABSTRAK

Kesalahan dalam menyelesaikan persamaan kuadrat sering terjadi pada siswa sekolah menengah dan dapat berdampak signifikan terhadap kemahiran mereka dalam matematika. Penelitian ini bertujuan untuk mengidentifikasi jenis kesalahan yang dilakukan oleh siswa kelas 10 serta faktor-faktor yang berkontribusi terhadap terjadinya kesalahan tersebut. Studi ini dilakukan di tiga sekolah menengah atas di Distrik Lebowakgomo, Provinsi Limpopo, dengan melibatkan sembilan puluh sembilan siswa yang mengikuti mata pelajaran Matematika, di mana sembilan di antaranya dipilih untuk diwawancarai. Data dianalisis secara kuantitatif melalui skor tes siswa serta secara kualitatif dengan analisis dokumen dan wawancara. Hasil penelitian menunjukkan bahwa kesulitan belajar siswa tercermin dalam kesalahan yang mereka buat, terutama yang berkaitan dengan kecerobohan, kesalahan dalam operasi numerik, urutan operasi, serta kesulitan dalam memahami dan mengoperasikan persamaan aljabar. Ketidakkonsistenan konseptual dan prosedural ini menghambat kemampuan siswa dalam memecahkan masalah. Implikasi dari penelitian ini adalah perlunya strategi pembelajaran yang lebih terarah untuk

mengatasi kesenjangan dalam pemahaman konseptual dan kelancaran prosedural guna meningkatkan pencapaian akademik siswa dalam Matematika.

Contribution to the literature

This research contributes to:

- Identify the common types of errors made by students while solving quadratic equations.
- Suggest targeted teaching strategies and interventions designed to address students' specific errors.
- Inform curriculum designers about the areas of quadratic equations that require more focused teaching, which leads to curriculum adjustments.
- Enhance the understanding of student errors in solving quadratic equations and provide practical solutions for improving academic performance in this critical area of mathematics.

1. INTRODUCTION

Understanding how to solve quadratic equations is critical to students' success when learning mathematics in school and beyond. Quadratic equations are key to other mathematics topics, yet, to students, this is difficult to understand or solve. In mathematics education, the cognitive difficulties that may delay students' understanding of specific topics are important to all stakeholders, curriculum designers, and practitioners [1]. The findings of this study will shed light on students' understanding and learning experiences. Most students find it difficult to solve these equations, which greatly impacts their performance because those who do not understand how to solve quadratic equations perform poorly in other mathematics topics.

Students need foundational knowledge in mathematics to advance to a higher learning level. The advantages of mathematics go beyond calculation; more significantly, when someone is proficient in the subject, their thinking becomes more critical and logical [2], [3]. Quadratic equations have significantly influenced the historical development of algebra and mathematical curricula worldwide [4]. Quadratic equations are regarded as essential in mathematics curricula in schools because they act as a link between mathematical topics like polynomials [5], functions [6], and linear equations [7] [8]. According to the Curriculum Assessment Policy Statement [9], the main objectives of mathematics education are for students to conduct research and find innovative solutions to problems.

Sarwadi and Shahrill [10] state that rather than teaching fundamental ideas and the reasoning behind the procedures, mathematics instruction in schools is typically concentrated on the rules and formulas to demonstrate to students how to obtain the right answers. Teaching students procedural skills will hinder their learning in the classroom and fail to provide them with the foundational mathematical knowledge they will need in the future. The researchers have observed students' common mistakes when attempting to solve quadratic equations. Didiş *et al.* [11] discovered that, while students were aware of some quadratic solving rules, they were not considering the reasons behind their actions or their mathematical correctness.

The rationale behind this topic is rooted in recognizing that errors in understanding and solving quadratic equations are common barriers to students' success in mathematics. Quadratic equations are a fundamental topic in grade 10 mathematics, and the ability to

solve them is essential for students to progress in mathematics and related subjects [12]. Many students struggle with key concepts of factoring [13]. These errors can stem from different sources, such as misconceptions, misunderstanding of the underlying principles, or lack of practice. By examining the types and causes of these errors, educators and researchers can identify specific areas where students have difficulties and then come up with interventions to address those challenges [14].

Research indicates that errors made by grade 10 students when solving quadratic equations can generally be classified into three categories: misinterpretation of mathematical language, unchecked solutions, and technical errors [15]. According to Makgakga [16], some mistakes students make when solving problems may be brought about by negligence, misreading text or symbols, or lack of pertinent background knowledge regarding the mathematical topic or concept in question. Research by Zakaria and Maat [17] reported that students make errors common in alteration and processing skills while solving quadratic equations. On the other hand, Didis and Erbas [6] investigated the performance and difficulties of students in expressing and solving quadratic equations. Studies by Didiş *et al.* [11] and Nielsen [18] talk about students who have not mastered basic algebraic principles, such as terms and simplifying expressions, tend to apply incorrect methods when dealing with quadratic equations, leading to errors.

Furthermore, Tall *et al.* [19] envisaged gathering their data through a concept map made up of students that involved their knowledge of quadratic equations. Their findings show that students used the quadratic formula with little understanding. In essence, it is significant to identify specific learning barriers and provide solutions that will improve students' mathematical understanding and performance in grade 10, ultimately helping them succeed in the subject.

Research focused on challenges or mistakes made by students in mathematics has been carried out, and those mistakes have been classified. Dhlamini and Kibirige [20] said that some students use shortcuts to solve mathematical problems, which leads to mistakes. Didiş *et al.* [11] discovered that students attempted to apply rules incorrectly when converting one form of an equation to another by examining student work on quadratic equations. In their research, Didis and Erbas [6] discovered that certain students struggle with multiplication facts, which hinders their ability to identify factors for expressions in the format $ax^2 + bx + c$ quickly. Limited studies have been concerned with understanding the difficulties students experience in solving quadratic equations. Due to the problems encountered by students, the researchers chose to find what types of challenges these students faced to know what to highlight when teaching quadratic equations. The study aimed to investigate the nature of errors made by students, such as errors when solving quadratic equations.

Solving quadratic equations by factorization requires students to find factors quickly, which burdens students [19]. Therefore, this research intended to investigate the nature of errors committed by students, find examples of such errors when solving quadratic equations, identify factors influencing the academic performance of grade 10 students in quadratic equations, and determine cognitive factors related to improving students' understanding and application of quadratic equations in mathematics. Many studies have been conducted on errors in mathematics learning, including analysis of students' errors in understanding quadratic functions [17], identification of procedural errors in solving quadratic equations [11], and errors in using the factorization method in quadratic equations [18]. Several studies have also discussed the influence of misconceptions on students' understanding of algebra [16]. However, there have not been many studies that specifically analyze the types of errors and factors that cause students' difficulties in

solving quadratic equations at the 10th-grade level and provide comprehensive intervention recommendations. This study aimed to analyze the errors made by 10th-grade students in solving quadratic equations and identify the factors that cause them. If previous studies focused more on identifying certain errors or procedural analysis, this study attempted to link these errors with students' cognitive aspects and provide relevant teaching and curriculum development recommendations. Thus, this study is expected to improve students' conceptual understanding and support more effective mathematics learning.

2. METHOD

Understanding students' problem-solving proficiency in quadratic equations requires a research approach that captures their thought processes and challenges in real-world contexts. Qualitative research was chosen as the research approach to describe, collect, and analyze students' proficiency in solving quadratic equations. Qualitative researchers investigate phenomena in their natural environments to make sense of phenomena [21]. This approach helped the researchers describe existing realities as accurately as possible [16]. This study employed a phenomenological research design. Phenomenology is used to uncover and interpret individual experiences and represent them [18]. In this case, how students solve quadratic equations. The choice of a phenomenological research design was based on the research objective of conducting a thorough analysis of errors made by students when faced with questions regarding quadratic equations.

After receiving ethics approval, the research was conducted. The participants were 10th-grade students of both sexes, aged 15 to 16, studying mathematics at their respective schools. Students in Grade 10 from three schools in the Lebowakgomo Sub-district, Capricorn district, in the Province of Limpopo, South Africa, comprised the study's population. The three schools were coded as DK, LH, and JS. It was difficult to study and work with the whole population. Therefore, three students were sampled from each school out of 99 students of both sexes. The selection of students from the three schools aimed to produce credible and good data quality. The population of this study was 54 mathematics students from DK, 12 from LH, and 33 from JS. The participants were randomly selected. On the contrary, convenience sampling was used to select students for the interview. Convenience sampling includes participants who are readily available or easily encountered by the researcher and often rely heavily on volunteer subjects [22]. After consent was obtained from parents and students, the research was conducted.

The research instruments utilized were a mathematical test of quadratic equations and a semi-structured interview. A mathematics test consisting of nine questions was prepared. After the questions were created, the questions were then validated by several experts in the field: the mathematics department head, a lecturer, and the curriculum advisor for mathematics. Furthermore, the interview guidelines were used as a form of confirmation to analyze the errors made by students. A well-founded study must reveal what exists, and a vital instrument should measure what it is supposed to measure [18]. For students to complete the test, specific skills were required for each item, as shown in Table 1.

Table 1. The Items of the Test Instrument

Item	Indicator
1.1.1	Factorize by taking out a common factor.
1.1.2	Use two types of factorizations: common factors and difference of two squares, but factorize completely.
1.1.3	Use the difference of two squares to find the solution.
1.1.4	Factorize a trinomial.

1.1.5	Factorize by grouping in pairs.
2.1	Simplify and factorize the denominator and numerator.
2.2.1	Solve the equation by first equating to zero, factorizing a trinomial, and solving the equation.
2.2.2	Perform calculations to solve the equation.
2.2.3	Perform procedures of calculations before solving the equation.

Data were gathered through tests and interviews that student took in their classrooms, which served as an accommodating environment. The test was administered in an environment where no student received any assistance. Their scripts were carefully marked and analyzed, looking for any mistakes the students might have made. A subset of students was chosen for an interview based on their test responses. Mazhindu [22] opines that the advantage of interviews is that the researcher can find information that could not be obtained from a written solution. Thanks to the interviews, the researchers were able to gain a thorough grasp of the reasons behind the mistakes made by students. The semi-structured interview data and data from documents were analyzed using Ritchie and Spencer's [23] framework, which involves the following five steps.

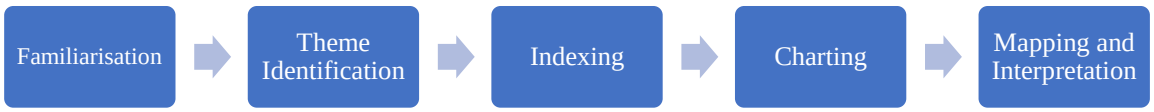

Figure 1. The Analysis Framework [23]

3. RESULTS AND DISCUSSION

The research findings illustrated the nature of students' errors when solving quadratic equations. Hence, the focus was mainly on students' errors, wrong procedures, and the reasoning processes behind the errors. The data was displayed after processing the test data, and the vignette and interview responses were presented.

Table 2. The Performance of Schools per Item

Item	School			Total
	DK (54 Students)	LH (12 Students)	JS (33 Students)	
1.1.1	11	4	15	30
1.1.2	1	0	3	4
1.1.3	0	1	0	1
1.1.4	10	7	25	42
1.1.5	1	0	0	1
2.1	0	2	4	6
2.2.1	4	5	8	17
2.2.2	2	0	4	6
2.2.3	0	1	3	4

Overall, student performance per item was generally poor, except for items 1.1.1 and 1.1.4, where they performed better. Regarding other items, most students attempted to solve the problems but abandoned them before reaching the answer. This suggests that they faced challenges in answering these questions or did not fully understand them.

Table 3. Students Responses to the Items (All Schools, N = 99)

Item	Solved with all steps (correct)	Attempt to solve and abandon (incomplete)	Failure to solve problems (incorrect)
1.1.1	29	4	66
1.1.2	4	26	69
1.1.3	0	5	94

1.1.4	45	10	44
1.1.5	1	0	98
2.1	6	45	48
2.2.1	16	17	66
2.2.2	6	20	73
2.2.3	3	3	93
Total	110	130	651

Based on Table 3, the data summarizes students' ability to answer the given questions. The results indicate that most students struggled to solve the problems correctly. Specifically, only 12.3% provided correct answers, while 14.6% gave incomplete responses, and the majority (73.1%) had incorrect answers. This suggests that students struggle to follow the correct procedures for solving quadratic equations.

A document analysis of students' scripts and calculations was conducted to better understand these difficulties. The analysis revealed three common errors: (1) failure to factorize using appropriate factoring methods, (2) failure to simplify expressions, and (3) failure to correctly solve quadratic equations. A key issue observed was that students often memorized factoring techniques without fully understanding the required procedures or the meaning of their solutions [18], [21].

3.1 Failure to Factorize Using Types of Factoring

Different methods are used when factorizing depending on the type of expression, as there are six types of factoring: the highest common factor, grouping, the difference of two squares, the sum or difference of two cubes, trinomials, and general trinomials. Some students struggled with factorization, answering questions without considering whether the chosen method was appropriate. Makgakga [16] says some students memorize those types of factoring without understanding what procedures to follow and what solution they have found when solving quadratic equations. The vignette below is an example.

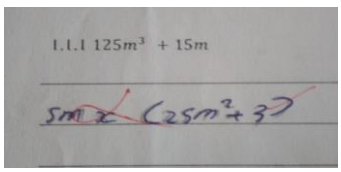

Figure 2. Factorization by Including x

The student took out the common factor, but he included ***x*** unexpectedly. This action emanated from the fact that he thought that when one is given a variable, the variable should be *x*. The common factor is *5m*, but the student decided to "factor out" *5mx*. It was a wonder where the student found the *x* from, as no x was given in the expression. Students need to know that variables cannot always be *x*. Expressions can have any variable. This does not mean that variable *x* is the only one used; all alphabet letters are used as variables in mathematics.

The researchers observed careless mistakes, where the students wanted to reach the answer without checking whether what they wrote was in line with the questions asked.

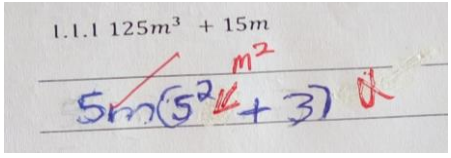

Figure 3. Removing Variables

Students use quick and easy methods to find answers in just a few steps, often relying on shortcuts that lead to errors [21]. For example, a student might simplify the expression ($125m^2 + 15m$) as $5m\ (52 + 3)$ without recognizing that the squared term (m^2) is missing inside the brackets. As a result, the student fails to see that their answer cannot be reversed to match the original expression. Similarly, another student may alter the given expression by introducing nonexistent variables to make it fit their approach, leading to incorrect solutions.

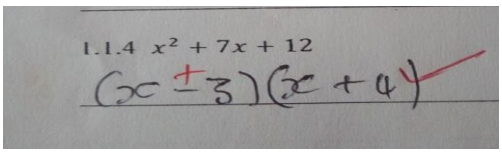

Figure 4. Ignoring the Signs Inside the Brackets

Figure 4 illustrates that some students struggle to correctly place the signs, particularly distinguishing between (-) and (+) after factoring. This difficulty often stems from challenges with multiplication, making it harder for them to quickly identify factors. Additionally, some students resort to using the quadratic formula for factoring, even when the expression is factorable [24].

3.2 Failure to Solve Quadratic Equations

Many students make errors when solving quadratic equations, indicating a lack of understanding of the solution process. Another challenge is their attitude toward mathematics; some find it difficult and resort to using any method just to provide an answer. Additionally, students often treat quadratic equations as if they were simple linear equations. They sometimes struggle to convert quadratic equations into standard form, as shown in Figure 5 below. As Didiş *et al*. [11] and Nielsen [18] said, students use procedures without understanding and struggle with aspects of solving quadratic equations that are not in standard form.

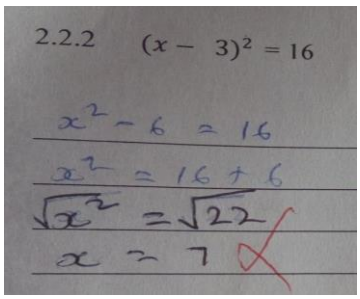

Figure 5. The Student's Incorrect Application of Methods

The student failed to see that $(x - 3)^2 = 16$ can be written as $(x - 3)(x - 3) = 16$ before multiplying and writing x as x^2, multiplied -3 by -2 to have -6. Here, the student applied the wrong methods to simplify the left-hand side. The student decided to square both sides as the next step is x2 = 22. This action was done because the student wanted to find the value of x from $\sqrt{x^2} = \sqrt{22}$. The student wrote $x = 7$ despite $\sqrt{22} \neq 7$. According to how the student wrote the expression as $\sqrt{x^2} = \sqrt{22}$, then $x = \pm 4$, not $x = 7$. The student imposed a radical sign without fully understanding its implications, demonstrating a fundamental misunderstanding of the procedure. This error highlights their failure to recognize that square roots yield positive and negative values and their reliance on incorrect methods without conceptual clarity.

3.3 Failure to Simplify

It was found that students failed to transfer correctly by changing the sign of a term when it was transferred from one side to the other. According to Didiş *et al.* [11], students incorrectly tried to transfer rules from one form of an equation to another form without understanding the meaning thereof. At least, at this level, the students must be able to simplify as it was done in lower grades. At the beginning of a lesson, educators must review previous concepts and relate them to the new concepts. Ignoring the previous concepts can cause students to interpret the concepts differently.

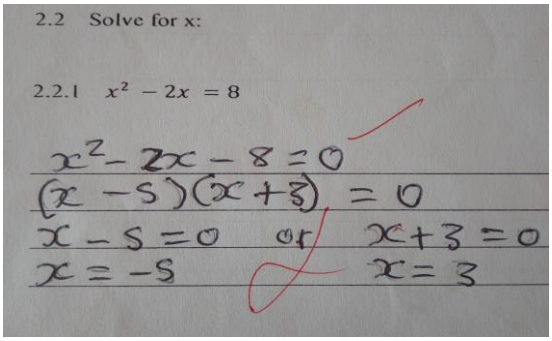

Figure 6. Failure to Change Signs After Transposing

The student knew that the equation should be written in standard form. However, they misunderstood the factoring process, believing the factors should add up to the last number (8) rather than recognizing that they must multiply by 8 and sum to the middle term. As a result, the student incorrectly identified -5 and +3 as factors since they add up to 8 without considering their product. Furthermore, when transposing -5 and +3, the student failed to change the signs, incorrectly concluding that x = -5 or x = 3 remained unchanged. This indicates a partial understanding of mathematical rules, as students sometimes apply concepts incompletely rather than fully grasping them.

Several researchers used tests and interviews to collect data on students' understanding of quadratic equations [11], [22], [25]. In an interview, questions were asked according to what students wrote in their scripts. During that process, it was evident that the students answered without checking if the method used was correct or not. Solving quadratic equations by factorization requires students to find factors quickly. Thus, it becomes a challenge to students [11].

Watanabe [26] said students use simple substitute approaches and make mistakes. In certain circumstances, students commit mistakes without realizing them, and if they are not acknowledged, they may result in further mistakes [24]. Students often make procedural errors while solving quadratic equations using factoring or the quadratic formula. Mamba [15] highlighted that procedural errors arise from a lack of mastery of foundational algebraic skills.

A student who introduced a variable (x) not written on the question said, "I made a mistake." Due to some students' attitude towards mathematics, they just use any method to give an answer. Another student introduced a radical sign (√) and used it inappropriately √ (x^2) = √22. The rule was applied incorrectly when converting from one form of an equation to another [11]. Many students made errors when simplifying or factoring quadratics, particularly with sign changes, coefficients, or expanding binomials. Errors in arithmetic calculations or simplification when solving equations is a serious problem. Hence, Nielsen [18] found that students' performance suffered due to reliance on rote memorization rather than understanding.

This study focused on errors and cognitive factors influencing students' problem-solving approaches when answering questions on quadratic equations. The findings revealed that students exhibited numerous errors and misconceptions, particularly in procedural understanding [18], [27]. Common errors identified included sign errors, calculation errors, factorization errors, simplification errors, rule misapplications, common factor errors, and meaningless solutions. Such errors are frequently reported in mathematics education research as common challenges. Makgakga [16] asserts that students with weak mathematical backgrounds are likelier to make numerous errors when solving mathematical problems. The findings of this study align with previous research, confirming that students continue to struggle with factorization—a challenge well documented in existing literature.

Many students struggled with basic arithmetic operations, such as addition, subtraction, multiplication, and division. This led to confusion when transferring variables or numbers, particularly regarding sign changes. Additionally, some students struggled with expanding algebraic terms correctly, while simplifying or grouping terms remained a challenge. These findings highlight persistent difficulties in understanding the underlying concepts of quadratic equations. Many studies suggest a lack of deep conceptual understanding contributes to procedural errors. This study supports the findings of Mamba [15] and Makgakga [16], both of whom emphasize the importance of conceptual comprehension in algebra. Students who fail to grasp different factorization methods tend to make frequent errors when solving quadratic equations.

The high frequency of errors observed in students' solutions suggests that many do not fully understand how to solve quadratic equations. Instead, they rely on memorizing rules and procedures without meaningful comprehension. Makgakga [16] argues that without conceptual understanding, students struggle to apply correct procedures when answering questions. This study also found that some students could not determine whether their final answers should be positive or negative, particularly when using fundamental arithmetic operations (+, −, ×, ÷). Furthermore, some students could not convert quadratic equations into standard form.

Understanding the zero-product property is crucial for solving quadratic equations through factorization. If students grasp this concept, they can effectively apply it when solving for unknowns. Nielsen [18] notes that one common error occurs when students translate an equation from standard to factored form but fail to correctly apply the zero-product property. Some students also incorrectly use distributive rules in cases where they are unnecessary.

Sign errors were prevalent when students developed algebraic expressions. The study revealed that most mistakes stemmed from conversion errors and procedural misunderstandings. Due to carelessness, some students applied incorrect mathematical rules without verifying their relevance to the problem. Others mistakenly treated dissimilar terms as if they were similar. Conceptual knowledge is essential, as it helps students understand how to apply a procedure and why and when to use it [22]. The difficulty students experienced in problem-solving was influenced by several factors, including failure to focus on key information within a problem statement and weak reasoning or recall of relevant mathematical knowledge [28], [29].

The finding that many Grade 10 students struggle with factoring and sign errors aligns with previous research [11], [18], [22], [30], which has consistently identified the improper use of factors and signs as a recurring issue at this level. While the study's results are largely consistent with existing literature on the challenges of solving quadratic

equations, observed discrepancies may be attributed to differences in teaching methods or assessment approaches.

This study highlighted areas where students struggle with quadratic equations, particularly factoring and solving equations. As a result, educators can adjust their teaching strategies to better address these challenges [16]. The findings suggest that students are not adequately prepared for solving quadratic equations due to gaps in their prior algebraic knowledge. Makonye and Nhlanhla [24] emphasize that students enter a new grade with some foundational knowledge from previous levels. However, weaknesses in factoring skills indicate the need for reinforcing basic factoring techniques in the Grade 9 curriculum to ensure better preparedness for quadratic equations [24]. Educators and policymakers should prioritize strengthening foundational concepts before introducing quadratic equations. Mazhindu [22] also supports the argument that factoring errors are common, suggesting that curriculum adjustments should emphasize algebraic factoring more before students encounter quadratic equations in Grade 10.

Although this study provides valuable insights, several limitations must be acknowledged. First, the sample was limited to three schools in Capricorn South District, Limpopo Province, South Africa. Additionally, the study relied on written tests and interviews to assess students' understanding, which, while allowing for real-time questioning and follow-ups with selected students, may not fully capture the depth of their misconceptions. Moreover, the research primarily focused on errors in solving quadratic equations and factoring, leaving other important aspects unexplored.

Future research should consider expanding the sample to other districts and examining additional critical aspects of quadratic equations to improve the generalizability and depth of findings. Further studies could also investigate other contributing factors and provide practical recommendations for enhancing teaching strategies, curriculum development, and instructional practices. The goal is to help students overcome common errors in solving quadratic equations and strengthen their mathematical proficiency.

4. CONCLUSION

This study provides recommendations for teaching and learning in the classroom and directions for future research. Many students struggle to determine which mathematical rules to apply and how to use them correctly. As a result, their answers often reflect an understanding of certain aspects of factoring but not the original problem. The research indicates a tendency among students to apply procedures mechanically without fully grasping the underlying concepts. To improve learning, students must be explicitly taught that solving quadratic equations requires factoring as a first step. Encouraging students to recognize and analyze their mistakes is a powerful way to engage them in learning. When students actively interact with their errors, they attach deeper meaning to mathematical concepts. Another key challenge in learning quadratic equations is students' difficulty identifying mistakes and their varying willingness and ability to correct them.

The study highlights significant difficulties students face in solving quadratic equations. It underscores the need for educators to create a supportive classroom environment where students feel comfortable expressing their challenges, building on prior knowledge, and engaging in discussions. Problem-solving lessons should be dynamic and interactive, incorporating discussions, group work, and regular board demonstrations to address common difficulties. Additionally, curriculum developers should allocate more time to teaching quadratic equations, ensuring students can fully grasp all related concepts. This study can benefit educators, curriculum developers, and the broader education community by improving the teaching and learning of mathematics, not only in South

Africa but globally. By addressing student errors and misconceptions, educators can better support learners in mastering quadratic equations.

AUTHOR CONTRIBUTION STATEMENT

VM contributed to conceptualizing the study, designing the methodology, conducting the data analysis, and drafting the manuscript. MPR provided guidance on the research design, helped with data interpretation, and revised and refined the manuscript.

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