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Data-driven analysis of parental involvement and mathematics achievement via engagement and efficacy

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Abstract

This study examined the relationships among parental involvement, learning engagement, self-efficacy, and mathematics achievement to identify actionable factors for improving student performance. A data-driven quantitative design was employed using secondary data from 354 respondents, analyzed through nonparametric methods, mediation modeling, association rule mining, and exploratory predictive modeling with classification and regression trees. Reliability analysis confirmed strong internal consistency for all scales, and descriptive statistics indicated generally high levels of parental involvement, engagement, and self-efficacy among participants. Correlation and mediation analyses revealed that parental involvement significantly influenced mathematics achievement both directly and indirectly through learning engagement and self-efficacy, with combined mediators accounting for more than half of the total effect. Prescriptive analytics highlighted engagement and self-efficacy as multidimensional levers (behavioral, emotional, and cognitive) for improvement, while predictive models demonstrated good classification performance and meaningful reductions in error for continuous achievement scores. These findings underscore the importance of integrated strategies that strengthen family-school partnerships while simultaneously fostering engagement and confidence to optimize mathematics outcomes. The study concludes that parental involvement, learning engagement, and self-efficacy are critical, interrelated factors in mathematics achievement and recommends multilevel interventions while acknowledging limitations of cross-sectional secondary data. Future research should employ longitudinal and experimental designs to establish causality and validate these findings across diverse contexts.

Keywords: *educational data mining; family-school partnership; motivation; student engagement; student performance*

INTRODUCTION

Mathematics achievement is widely recognized as critical determinant of students' academic successful and future career opportunities, influencing educational trajectories and professional readiness (Wang & Wei, 2024). Despite decades of reform, disparities in mathematical performance remain a persistent challenge in educational systems prompting researchers and practitioners to identify factors that can enhance student

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outcomes. Among the factors, parental involvement (PI) has consistently emerged as a significant external influence, fostering supportive home-school relationships and creating conducive learning environments. Parental math support has been shown to foster engagement through self-efficacy and enjoyment, reinforcing motivational pathways (Sağkal & Sönmez, 2022). Meta-analytic evidence further confirms that parental expectations are a powerful component of involvement influencing achievement (Jeynes, 2022). At the same time, parental involvement can exert both positive and negative effects depending on its form and differentiation (Bacskai et al., 2024).

Educational psychology literature highlights two internal factors – Learning Engagement (LE) and Mathematics Self-Efficacy (SE) – as potential mediators in academic performance. LE is multidimensional, encompassing behavioral (persistence, effort), emotional (interest, enjoyment), and cognitive (strategic learning) dimensions, each strongly linked to improved achievement (Metu, 2024). Student engagement has been found to significantly influence mathematics achievement among secondary school learners (Maamin, Maat, & Iksan, 2022). SE, defined as students' confidence in their ability to master mathematical tasks, is a robust cognitive predictor of persistence and success in mathematics (Blessing, 2024). Large-scale assessments confirm that mathematics self-efficacy strongly predicts achievement outcomes (Yang, Maeda, & Gentry, 2024), while academic motivation and affective engagement towards mathematics are mediated by self-efficacy, highlighting its central role (Valenzuela- Peñuñuri et al. 2024). Mathematics self-efficacy and parental involvement jointly predict achievement outcomes (Apa & Antiquina, 2022), and TIMSS 2023 results highlight the importance of self-confidence in mathematics achievement (Anderson & Lopez, 2024). Together, these constructs provide motivational pathways through which parental involvement may influence achievement (Corvera et al, 2024).

Theoretical frameworks further clarify these mechanisms. Self-determination theory emphasizes that autonomy-supportive parental practices foster intrinsic motivation and engagement (Metu, 2024), with autonomy support linked to emotional intelligence (Gómez-López et al., 2025). Recent studies reaffirm this framework as central to understanding student motivation (Mok Soon Sim & Rahmat, 2025). Meanwhile, Social-Cognitive Theory posits that efficacy beliefs are proximal determinants of performance (Zakariya, 2022). Together, these perspectives suggest that parental involvement does not simply exert a direct influence on mathematics achievement; rather, it operates through motivational pathways that strengthen engagement and self-efficacy.

Integrating these perspectives provides a coherent rationale for the study's hypotheses. Specifically, parental involvement is expected to enhance mathematics achievement both directly and indirectly through learning engagement and self-efficacy. Grounded in this framework, the current study examines these pathways employing advanced nonparametric mediation and data mining techniques. Authentic parent engagement is increasingly recognized as essential for reimagining teacher education and strengthening school partnerships (Ryan, 2025).

The originality of this study lies in its integration of the Knowledge Discovery in Database (KDD) process with nonparametric data mining and mediation modeling to analyze secondary educational datasets (Metu, 2024). By employing flexible, distribution-free methods-such as Orange data mining workflows and mediation analysis in R-this research aims to uncover subtle, potentially non-linear relationships and interaction effects that conventional models may overlook. In doing so, the study advances methodological innovation while providing evidence-based guidance for improving

mathematics achievement through parental and motivational interventions.

Guided by this rationale, the study addresses the following research questions;

1. What nonparametric patterns describe the relationship between parental involvement and mathematics achievement?
2. To what extent does learning engagement explain this relationship through mediation analysis?
3. What role does mathematics self-efficacy play in predicting differences in achievement?
4. What actionable insights can be derived from the combined mediating roles of learning engagement and self-efficacy to maximize performance through parental engagement approaches?

This research is important because mathematics achievement remains a critical determinant of students' academic success and future career opportunities, yet disparities persist despite decades of reform (Wang & Wei, 2024). While parental involvement has been widely recognized as a positive influence, the specific pathways through which it enhances achievement – particularly via learning and self-efficacy – are not fully understood. By employing advanced nonparametric mediation and data mining techniques, this study addresses methodological gaps in prior research (Metu, 2024) and provides more nuanced evidence about how parental support interacts with motivational factors to shape mathematical outcomes. For readers, the study offers both theoretical and practical benefits: it integrates self-determination theory, which emphasizes autonomy-supportive parental practices fostering intrinsic motivation and engagement (Metu, 2024), and social-cognitive theory, which posits that efficacy beliefs are proximal determinants of performance (Zakariya, 2022) while providing actionable insights for educators, parents, and policymakers to design parent-school collaboration programs that align home routines with classroom goals, reinforce persistence and attentiveness, and build students' confidence in mathematics.

METHOD

Research design

This study employed a quantitative data-driven design guided by the Knowledge Discovery in Databases (KDD) framework. The analysis examined both direct and mediated relationships among parental involvement, learning engagement, self-efficacy, and mathematics achievement. To capture complex, potentially non-linear patters, nonparametric statistical procedures and mediation modelling were prioritized over traditional parametric approaches. Unlike parametric methods, which assume normality and linearity, nonparametric techniques are distribution-free and more robust in handling skewed or multimodal educational data. Nonparametric causal mediation tools further enhance methodological robustness and efficiency in educational contexts (Hejazi et al., 2022). This methodological choice ensures that subtle interaction effects are not obscured by restrictive assumptions.

Data source

Secondary datasets were obtained from Mendeley Data titled Effect of Parental Involvement on Students' Achievement in Mathematics: Roles of Learning Engagement and Self-Efficacy (Version 1; DOI: 10.17632/zbd8wj942y.1). The dataset included 354

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student respondents, with measures of parental involvement, learning engagement, self-efficacy, and mathematics achievement. Parental involvement (PI) was operational as academic support and communication; learning engagement (LE) was defined as behavioural (effort, persistence), emotional (interest, enjoyment), and cognitive (strategic learning) dimensions; self-efficacy (SE) was measured as confidence in mathematical tasks; and achievement was assessed through standardized test scores or course grades. The use of secondary data was justified by its comprehensive coverage of motivational and achievement-related variables, providing a valid basis for testing mediation pathways. Secondary datasets also allow for replication and methodological innovation research (Panchenko & Samovilova 2020), though reliance on cross-sectional data imposes limitations on causal inference and generalizability (Johnston, 2014).

Data analysis

Data preparation involved cleaning and organizing the dataset to ensure accuracy and consistency. Missing values were addressed using appropriate imputation methods (Little & Rubin, 2019), and reliability was tested using Cronbach's alpha to confirm internal consistency of the scales (Tayakol & Dennick, 2011). Outliers were managed to reduce bias, and variables were standardized to allow meaningful comparisons across constructs. These steps ensured that the dataset was suitable for advanced nonparametric analysis.

Analyses were conducted in two stages. First, descriptive and correlational analyses were performed to identify general patterns and associations among variables. Second, mediation models were tested to examine whether learning engagement and self-efficacy explained the relationship between parental involvement and mathematics achievement. Data mining-based prediction models have shown to effectively forecast student performance in sustainable learning contexts (Stanevicience et al, 2024). Educational data mining has been widely applied to predict academic performance through survey-based approaches (Batool et al., 2023) with updated surveys highlighting methodological advances that strengthen predictive validity (Romero & Ventura, 2020). Integration of EDM models into web-based systems improves prediction of high school performance and supports intervention design (Phauk & Okazaki, 2021). KDD techniques have further demonstrated practical utility in educational program design, such as applications to student stress satasets (Pagudpud, Soriano, & Serrano, 2021).

To strengthen the robustness of these mediation results, nonparametric bootstrapping and rank-based mediation were employed. Compared to parametric mediation, which relies on normality assumptions, these nonparametric approaches provide distribution-free estimates and greater accuracy in small or skewed samples. This explicit comparison highlights the methodological value of the study: by rejecting restrictive parametric assumptions, the analysis captures more authentic patterns in educational data.

In addition to mediation analysis, exploratory data mining techniques were applied to identify prescriptive patterns and predictive models. Association rule mining was used to highlight conditions linked to high achievement, while classification and regression trees were employed to predict achievement outcomes based on parental involvement, engagement, and self-efficacy. These models were evaluated using cross-validation to ensure reliability. Together, these methods extend beyond explanation to provide actionable insights for practice.

Tools and software used

The study utilized Orange data mining workflows, RStudio, and Python scripts to conduct

nonparametric analyses, mediation modeling, association rule mining, and predictive modelling, ensuring robust handling of complex educational data. These tools supported the Knowledge Discovery in Database (KDD) process, enabling reliability testing, imputation, visualization, and classification. Additionally, Microsoft 365 Copilot was used solely as an AI-powered writing assistant for clarity and consistency; its use was limited to language enhancement and did not influence data analysis or interpretation.

Ethical consideration

This study used secondary data with no direct participation from human subjects. All records were anonymized to ensure privacy and confidentiality , and no personally identifiable information was included in the analysis. Data access complied with licensing terms in Mendeley and was supported by formal approval from the data owner. The researcher adhered to responsible reporting practices, avoiding data fabrication, manipulation, or misrepresentation, and documented analytic decisions transparently.

RESULTS AND DISCUSSION

Nonparametric patterns on the relationship between parental involvement and mathematics achievement

Table 1

Reliability Statistics (Cronbach's Alpha for PI, LE, and SE)

Scale	N_items	N_observations	Cronbach's α
Parental Involvement (PI)	8	354	0.902
Learning Engagement (LE)	6	354	0.899
Mathematics Self-Efficacy (SE)	6	354	0.898

Reliability analysis confirmed excellent internal consistency across all scales, with Cronbach's alpha values above 0.89 (see Table 1), exceeding the conventional threshold of 0.70. This indicate strong measurement reliability.

Table 2

Descriptive Statistics for PI, LE, SE, and MA

Variable	N	Mean	Median	Mode	SD	IQR	Min	Max
Parental Involvement (PI)	354	25.79	27	32	6.393	6.0	8	32
Learning Engagement (LE)	354	19.47	21	24	5.047	5.0	6	24
Mathematics Self-Efficacy (SE)	354	19.19	21	24	4.914	5.0	6	24
Mathematics Achievement(MA)	354	21.71	22	22	2.843	2.0	15	31

Note: n = sample size; SD = Standanrd Deviation; IQR = Interquartile Range; Min = Minimin; Max = Maximun

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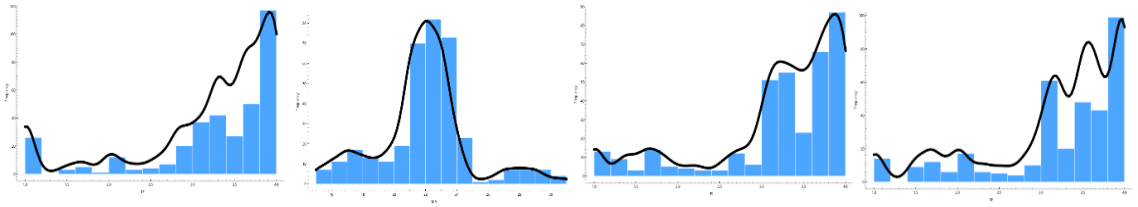
Figure 1
Kernel Density Plots for PI, LE, SE, and MA



Descriptive statistics (Table 2)revealed generally high levels of parental involvement (PI), learning engagement (LE), and self-efficacy (SE), while mathematics achievement (MA) was more moderately distributed. Kernel density plots (Figure 1) reinforced these findings, and quantitative descriptions provided further detail. PI scores exhibit moderate positiven skewness (skewness=0.5), indicating that most parents reported high involvement with fewer reporting low levels. LE showed multimodality across its dimenstions: behavioral engagement was approximately normal, emotional engagement revealed a bimodal pattern with distinct clusters of students reporting high versus low interest, and cognitive engagement was moderately skewed toward higher values. SE displayed multimodality, with one subgroup reporting very high confidence and another reporting moderate confidence in matehmatics tasks. Such ceiling effects are common in self-report measures (Metu, 2024), and the multimodality in SE suggests heterogeneous subgroups of confidence in mathematics (Zakariya, 2022; Street et al., 2024). MA scores were close to normal, with slight positive skewness (skewness = 0.42) and minor negative kurtosis (-0.18), suggesting a relatively balanced distribution with slightly flatter tails.

Consistent with these results, student engagement has benn found to significantly influence mathematics achievement (Maamin et al., 2022), reinforcing teh descriptive findings here. Moreover, combined influences of parental involvement, engagement, and peer support mirror the multidimensional pathways identified in thi study, highlighting the interplay of family and social factors in shaping mathematics outcomes(Abu Bakar et al., 2021).

Table 3
Correlation Matrix (Spearman's ρ) among PI, LE, SE, and MA

Pair	Spearman ρ	95% CI Lower	95% CI Upper	p- value	Interpretation
PI ↔ LE	0.598	0.522	0.673	< 0.001	Moderate positive correlation
PI ↔ SE	0.566	0.484	0.645	< 0.001	As PI increases, LE tends to increase moderately
PI ↔ MA	0.748	0.686	0.800	< 0.001	Moderate positive correlation
LE ↔ SE	0.447	0.351	0.532	< 0.001	PI and SE are positively related, but slightly weaker than PI-LE
LE ↔ MA	0.714	0.648	0.778	< 0.001	Strong positive correlation
SE ↔ MA	0.708	0.649	0.759	< 0.001	PI and MA have a strong correlation

Note: CI = Confidence Interval

Figure 2
Scatter Plots illustrating pairwise relationships

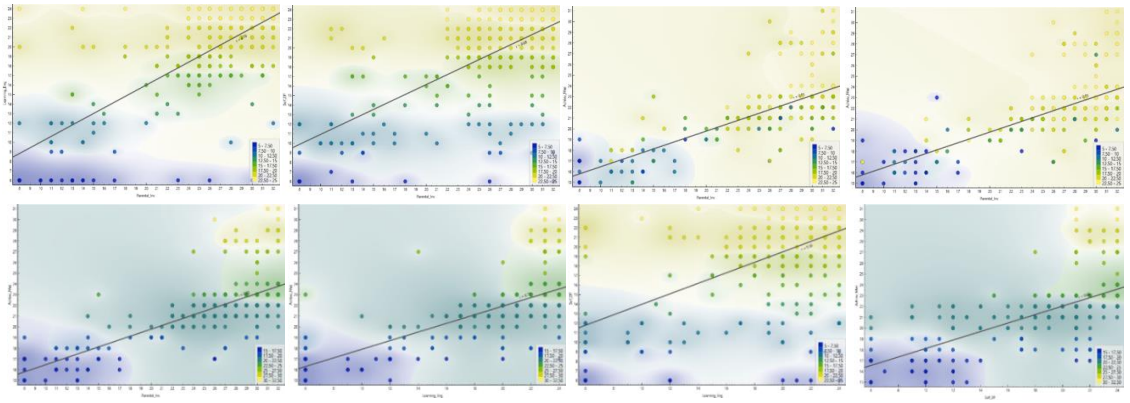
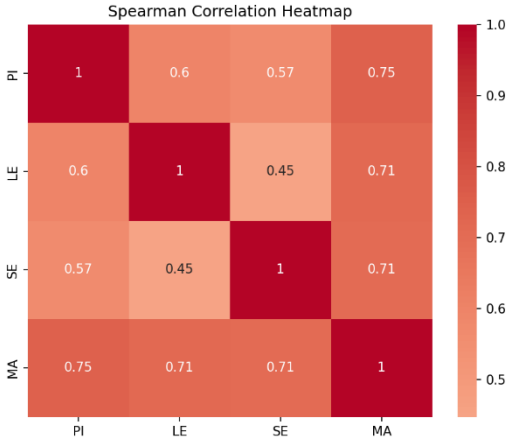


Figure 3
Correlation Heatmap showing strong strength of associations



Spearman's correlations further demonstrated strong positive associations between PI and MA (ρ ≈0.75) supported by scatter plots (Figure 2) and a correlation heatmap (Figure 3). This prominent PI-MA link aligns with meta-analytic evidence that parental involvement is a powerful predictor of achievement outcomes (Wang & Wei, 2024; Huang et al., 2021). Beyond this general pattern, recent studies highlight that the effects of parental involvement can be bth positive and negative depending on its form and differentation, explaining variability in achievement outcomes across contexts (Bacskai et al., 2024). Similarly, direct parental involvement has been hown to enhance mathematical skills and performance, reinforcingthe strength of the PI—MA pathway observed in this study (Corvera et al., 2024). Moreover, metaanalytic findings confirm that parental expectations amplify achievement, consistent with the strong correlation between PI and MA identified here (Jeynes, 2022).

Collectively, these results answer RQ1 by showing that PI is strongly associated with MA, with nonparametric patterns confirming variability in engagement and efficacy. This underscores the central role of family support in mathematics performance and highlights the importance of motivational pathways in explaining achievement differences.

Overall, the analysis confirms excellent reliability, high levels of parental

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involvement and motivational factors, and strong positive associations among PI, Le, Se, and MA, with PI as the most influential predictor. These findings emphasize the critical role of parental involvement and the mediating effects of engagement and self-efficacy, suggesting that integrated strategies targeting both family support and student motivation can enhance mathematics achievement.

Mediation analysis of learning engagement in explaining the relationship between variables

Table 4
Mediation Analysis for Learning Engagement (LE) as Mediator

Scale	Indirect	95% CI Low	95% CI High	A	b	c′	c_total
Original	0.918	0.632	1.220	0.798	1.150	1.726	2.644
Rank	0.245	0.187	0.311	0.596	0.411	0.495	0.740

Note: A path = PI to LE; b path = LE to MA; c'path = Direct effect of PI on MA; c_total = Total effect.

Table 4 presents the mediation analysis examining learning engagement (LE) as a mediator between parental involvement (PI) and mathematics achievement (MA). The indirect effect of PI on MA through LE was statistically significant (Indirect = 0.918, 95% CI [0.632, 1.220]. This effect was supported by a strong PI → LE path (a=0.798) and a substantial LE → MA path (b= 1.150). The direct effect of PI on MA remained positive (c' = 1.726), indicating partial mediation. Rank-based estimates confirmed the robustness of these findings, showing a smaller but reliable indirect effect (Indirect = 0.245, 95% CI [0.187, 0.311] with consistent path coefficients (a=0.596; b=0.411). These results demonstrate that learning engagement explains a meaningful portion of the relationship between parental involvement and mathematics achievement, consistent with recent evidence that engagement functions as a motivational pathway to achievement (Blessing, 2024; Metu, 2024).

The partial mediation suggests that while PI exerts a direct influence on achievement, its effect is amplified when students exhibit higher levels of engagement-manifested in persistence, attention, and active participation. This interpretation is consistent with motivational frameworks such as self-determination theory (Metu, 2024) and with empirical studies showing that parental support enhances student motivation and persistence in mathematics (Huang et al., 2021). The consistency between original and rank-based estimates strengthens the validity of the mediation effect, underscoring that engagement is a reliable pathway through which parental involvement enhances mathematics outcomes. This further supported by meta-analytic findings and cross-cultural studies that highlight the synergistic role of parental support and student engagement in mathematics learning (Wang & Wei, 2024). Moreover, predictive analytics research confirms that nonlinear effects of PI on achievement are often mediated by motivational constructs such as engagement and self-efficacy (Jiang et al., 2023; Djekourmane et al., 2025).

These findings align with prior evidence showing that student engagement significantly influences mathematics achievement (Maamin et al., 2022). In addition, serial mediation pathways involving parental support, self-efficacy, and enjoyment reinforce the role of engagement as a motivational mechanism, highlighting how parental involvement indirectly strengthens achievement through motivational constructs (Sağkal & Sönmez,

2021). Similarly, affective engagement mediated by self-efficacy parallel the indirect effects observed in this study, underscoring the multidimensional nature of engagement (Valenzuela- Peñuñuri et al. 2024).

From pedagogical perspective, the results suggest that structured parent-school communication, particularly when aligned with weekly mathematics goals and home study routines, can reinforce student engagement. Schools may consider designing programs that encourage parents to monitor progress, provide motivational support, and establish routines that cultivate persistence and attentiveness. Such practices not only strengthen engagement but also contribute to sustained improvements in mathematics achievement (Mondigo & Ucang, 2025).

Overall, the mediation analysis underscores that parental involvement enhances mathematics achievement both directly and indirectly by fostering learning engagement, suggesting that interventions should prioritize strengthening parent-school collaboration as a means of cultivating student persistence, attentiveness, and active participation.

The role of mathematics self-efficacy in predicting achievement differences

Table 5
Mediation Analysis for Self-Efficacy (SE) as Mediator

Scale	Indirect	95% CI Low	95% CI High	A	b	c′	c_total
Original	0.749	0.573	0.959	0.697	1.070	1.895	2.644
Rank	0.234	0.188	0.295	0.563	0.416	0.506	0.740

Note: A path = PI to SE; b path = SE to MA; c'path = Direct effect of PI on MA; c_total = Total effect.

Table 5 presents the mediation analysis with mathematics self-efficacy (SE) as a mediator between parental involvement (PI) and mathematics achievement (MA). The indirect effect of PI on MA through SE was statistically significant (Indirect = 0.749, 95% CI [0.573, 0959]), supported by a positive PI→ SE path (a=0.697) and a substantial SE →MA path (b=1.070). The direct effect of PI on MA remained positive (c' = 1.895), indicating partial mediation. Rank-based estimates corroborated this pathway, showing a smaller but reliable indirect effect (Indirect = 0.234, 95% CI [0.188, 0295]) with consistent path coefficients (a=0.563; b=0.416). These findings confirm that mathematics self-efficacy explains a meaningful portion of the relationship between parental involvement and achievement, consistent across estimation methods.

The results suggest that parental involvement enhances mathematics achievement not directly but also indirectly by strengthening students' confidence in their ability to manage mathematical tasks. This pattern reflects the central role of efficacy beliefs in social-cognitive theory, which posits that self-efficacy is a proximal determinant of performance. Students with higher self-efficacy are more likely to persist, employ effective strategies, and achieve better outcomes in mathematics (Zakariya, 2022; Street et al., 2024). The mediation effect observed here is consistent with findings that academic confidence predicts performance through self-efficacy pathways (Meng & Zhang, 2023). Large scale analyses further confirm that mathematics self-efficacy is a robust predictor of achievement outcomes (Yang et al., 2024). Likewise, TIMSS 2023 results highlight the importance of self-confidence in mathematics achievement, reinforcing the mediating role of efficacy beliefs (Anderson & Lopez, 2024).

The partial mediation observed here indicates that while PI exerts a direct influence on achievement, its impact is amplified when students develop stronger efficacy beliefs.

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This is consistent with recent meta-analytic evidence showing that parental involvement contributes to mathematics achievement through motivational pathways (Blessing, 2024; Djekourmane et al., 2025). The robustness of the indirect effect across both original and rank-based estimates further supports the reliability of this mechanism.

From pedagogical standpoint, these findings underscore the importance of coupling parental involvement with classroom practices that explicitly build self-efficacy. Strategies such as scaffolded mastery experiences, informative feedback, and teacher modelling can reinforce students' confidence in their mathematical abilities (Metu, 2024). When parents and teachers coordinate efforts- through communication about goals, encouragement, and shared monitoring of progress-students are more likely to internalize efficacy beliefs that translate into higher achievement. Overall, the mediation analysis highlights that parental involvement enhances mathematics achievement both directly and indirectly by fostering learning engagement, underscoring the importance of coordinated efforts among schools, families, and policymakers.

Learning engagement and self-efficacy as joint mediators in the relationship between parental engagement and performance

Table 6
Mediation Analysis for Parallel Multiple Mediators (LE + SE)

Effect (Parallel Mediation: LE + SE)	Original Scale	95% CI	Rank (Nonparametric)	95% CI
Total effect (c_total)	2.644	—	0.740	—
Direct effect (c′)	1.130	—	0.329	—
Total indirect (LE + SE)	1.514	[1.250, 1.829]	0.411	[0.351, 0.483]
Specific indirect via LE	0.832	[0.592, 1.092]	0.200	[0.157, 0.267]
Specific indirect via SE	0.682	[0.524, 0.880]	0.209	[0.161, 0.255]

Note: CI = Confidence Interval

The parallel mediation analysis revealed that parental involvement (PI) influenced mathematics achievement (MA) both directly and indirectly through learning engagement (LE) and self-efficacy (SE). The combined indirect effect was substantial (Indirect = 1.514, 95% CI [1.250, 1.829], accounting for approximately 57% of the total effect. Specific indirect effects indicated that LE (Indirect = 0.832, 95% CI [0.592, 1.092]) and SE (Indirect = 0.682, 95% CI [0.524, 0.880]) each contributed significantly. Rank-based estimates corroborated these findings, with reliable indirect effects for both mediators.

Table 7
Distribution of Achievement Tertiles (MA)

MA Tertile	Count	Percent
Low	148	41.8%
Medium	155	43.8%
High	51	14.4%

Only 14.4% of students were in the top achievement tertile, highlighting a low base rate of high achievers.

Table 8

Association-rule mining (antecedents: PI/LE/SE; consequent: MA = high)

8.1 Rules under pre-registered thresholds

Criteria	Outcome
Support ≥ 0.10, Confidence ≥ 0.70, Lift ≥ 1.10	No rules met criteria

8.2 Exploratory (relaxed) high-lift signals (support ≥ 0.10)

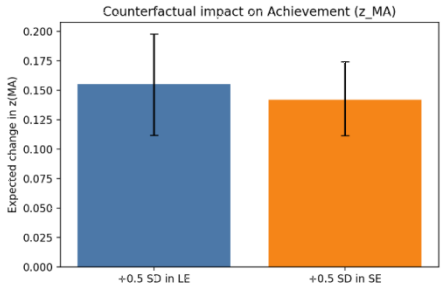
Antecedent (→ MA = high)	Support (rule)	Confidence	Lift
SE = high	0.107	0.384	2.66
LE = high	0.113	0.342	2.37

Note: Support ≥ 0.10. No rules met criteria for Confidence ≥ 0.70, Lift ≥ 1.10

Exploratory association-rule mining showed that students with high SE or high LE were 2.4-2.7 times more likely to belong to the high achievment group, despite the low base rate.

Figure 4

Counterfactual impact on achievement (z-MA)



Counterfactual simulations indicated that a 0.5 SD increase in LE predicted a 0.155 SD gain in achievement, while a similar increase in SE predicted a 0.142 SD gain.

Table 9

Standardized path model for achievement

Predictor	B(std)	Std. Error	p-value
z(PI)	0.320	0.0548	1.25×10^{-8}
z(LE)	0.310	0.0487	5.72×10^{-10}
z(SE)	0.283	0.0433	2.07×10^{-10}

Model: $z\ (MA) = \beta_{PI} z(PI) + \ \beta_{LE} z(LE) + \beta_{SE} z(SE) + \varepsilon$

where:

z (MA) : The standardized score of achievement (dependent variable).

z (PI), z(LE), z(SE) : Standardized scores of parental involvements, learning engagement, and self-efficacy (predictors).

β coefficients : Represent the relative contribution of each predictor to Achievement after controlling for the others.

E : The error term, capturing variation not explained by the predictors.

Explained Variance : $R^2 = 0.652$

Standard regression models confirmed that PI (β=0.320), LE (β=0.310), and SE (β=0.283) each had independent, positive associations with achievement, jointly explaining about 65% of the variance.

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Table 10
CART classification performance (MA ≥ median)

Fold	1	2	3	4	5
AUC	0.851	0.771	0.847	0.808	0.890
Mean AUC		0.8333			

Table 11
CART regression performance (continuous MA)

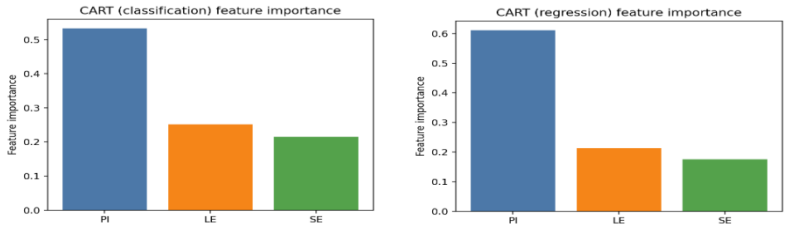
Fold	1	2	3	4	5
RMSE	2.516	2.207	2.032	2.171	1.966

Note: Mean RMSE = 2.178. Baseline RMSE = 2.843. Reduction vs. Baseline = 23.4%

Table 12
CART Models

Model	PI	LE	SE
Classification (Gini)	0.534	0.251	0.215
Regression (MSE)	0.612	0.212	0.175

Figure 5
CART Feature Importance (Classification and Regression)



CART classification and regression analyses yielded a strong predictive performance (mean AUC = 0.833; RMSE reduction ≈23%), with PI emerging as the most influential predictor, followed closely by LE and SE. These findings underscore the complementary mediating roles of learning engagement and self-efficacy in translating parental involvement into mathematics achievement. The substantial indirect effects suggests that PI enhances achievement not only through direct support but also by fostering behavioral engagement and motivational beliefs. This dual pathway is consistent with self-determination theory, which emphasizes autonomy-supportive environments for engagement (Metu, 2024; Gómez-López, et al., 2025), and with social-cognitive theory, which highlights self-efficacy as a proximal determinant of performance (Zakariya, 2022). Recent studies further reaffirm self-determination theory as a framework for understanding student motivation, aligning with the observed medating roles in this study (Mok Soon Sim & Rahmat, 2025).

Predictive analyses provided actionable insights: students with high engagement or efficacy are disproportionately represented in the top achievement tertile, aligning with prior evidence that are parental involveement strengthens both engagement and efficacy, leading to improved mathematics outcomes (Wang & Wei, 2024; Blessing, 2024; Djekourmane et al., 2025). The convergence of regression, mediation, and machine learning models reinforces the robustness of these pathways, suggesting that

interventions should simultaneously target engagement and efficacy to maximize achievement.

Practically, structured parent-school communication can reinforce study routines and goal-setting, thereby enhancing engagement (Hernández-Padilla et al., 2023). At the same time, parental practices emphasizing effort-based praise, scaffolded mastery experience, and modeling can strengthen self-efficacy (Street et al., 2024). Integrating these strategies offers a dual pathway to achievement, where behavioral persistence and motivational confidence work in tandem to elevate mathematics performance.

Several limitations of this study must be acknowledged. First, the reliance on cross-sectional secondary data restricts casual inference and reduces control over variable selection and measurement precision. Second, the use of self-report measures may introduce bias and ceiling effects, particularly in constructs such as parental involvement and self-efficacy. Third, the findings may not generalize beyond the sampled population, as contextual and cultural differences could influence both parental involvement and student motivation. These limitations should be considered when interpreting the results and their implications, and they highlight the need for future research employing longitudinal designs, primary data collection, and diverse samples to strengthen the robustness and generalizability of conclusions.

CONCLUSION

The study demonstrated that parental involvement (PI) significantly influences mathematics achievement (MA) both directly and indirectly through the complementary mediating roles of learning engagement (LE) and self-efficacy (SE). The findings highlight that achievement is not solely a product of parental support nut also of the motivational pathways it fosters- behavioral persistence, attentiveness, and confidence in mathematical abilities. These dual mechanisms are consistent with self-determination theory, which emphasizes autonomy – supportive environments for engagement, and with social-cognitive theory, which identifies self-efficacy as a proximal determinant of performance. Recent studies reaffirm self-determination theory as a framework for understanding student motivation, aligning with the mediating roles observed here. Predictive and prescriptive analysis further confirmed that students with high engagement and efficacy are disproportionately represented in the top achievement tertile, consistent with the evidence that parental involvement strengthens both pathways to improve mathematics outcomes. The convergence of regression, mediations and machine learning models reinforces the robustness of these findings, suggesting that interventions should simultaneously target engagement and efficacy to maximize achievement. Methodologically, the integration of nonparametric mediation and educational data mining approaches demonstrates the value of advanced analytic techniques in uncovering nonlinear effects and providing actionable insights.

Based on these results, multilevel interventions are recommended to maximize mathematics performance. For educators, classroom practices should integrate structured active-learning routines, scaffolded mastery experiences, and informative feedback to strengthen engagement and efficacy. For parents, consistent communication with teachers, effort-based praise, and establishment of study routines can reinforce persistence and confidence at home. For policymakers, institutionalizing family-support partnerships that emphasize both engagement and efficacy development will ensure equitable access to achievement-enhancing practices across diverse contexts.

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Looking ahead, future research should use longitudinal and experimental designs to establish causal links between parental involvement, learning engagement, self-efficacy, and achievement, and test integrated interventions through adaptive approaches. Studies should replicate findings across diverse contexts to assess generalizability and explore moderators such as socioeconomic status and school climate. Expanding mediation models to include additional motivational processes and moderated pathways will clarify mechanisms. Predictive and prescriptive analytics should advance with interpretable models, realistic thresholds, and rigorous validation, while technology-enabled strategies and equity-focused personalization should be leveraged to scale interventions effectively and ensure benefits for all learners.

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