Available online at
http://smrj.uitm.edu.my/index.php

e-ISSN: 0128-1089

Social and Management Research Journal 22(2) 2025, 71–89.

Social and Management Research Journal

Enhancing Teamwork and Statistical Knowledge Application through Problem-Based Learning: A Data-Driven Study in Information and Knowledge Management Education

Nur Atiqah Rochin Demong[1*], Masrur Mohd Khir[2]

[1,2]*Faculty of Business and Management, Universiti Teknologi MARA, 42300 Puncak Alam, Selangor, Malaysia*

ARTICLE INFO

Article history:
Received 12 September 2024
Revised 14 November 2025
Accepted 15 December 2025
Online first 16 December 2025
Published 16 December 2025

Keywords:
problem-based learning
teamwork development
students' perception
application of statistics
learning process

DOI:
10.24191/smrj.v22i2 September.9861

ABSTRACT

This study investigates the relationship between problem-based learning (PBL) and the development of teamwork skills within business administration and management education. Specifically, it examines how PBL influences students' perception, understanding, and application of statistical concepts and how these cognitive factors shape their ability to work collaboratively. A robust analytical framework was employed, beginning with data extraction from online survey data collected using Google Forms, followed by systematic data cleaning, preprocessing, and feature selection to ensure dataset integrity. To empirically evaluate its effectiveness, a dataset comprising 102 students as respondents and 20 attributes, including demographics, learning perceptions, engagement indicators, and teamwork skills as the class attribute, was examined. The attributes capture diverse aspects such as concept comprehension, material suitability, lecturer indication, statistical language proficiency, communication, and interpersonal skills. Exploratory clustering (EM) identified four student groups, with total instances of each group being 46, 10, 36, and 10 instances, respectively. Two clusters show strong teamwork endorsement, one moderate, and one showing lower or neutral teamwork responses, suggesting that PBL's effect on teamwork is not uniform across learner subgroups. For feature selection, the results depicted that the top three attributes clearly emphasize the central role of interpersonal interaction in shaping students' perceptions of teamwork development; namely, the highest-ranked attribute is smooth collaboration and communication with colleagues, indicating that consistent effective peer interaction is the strongest determinant of teamwork skill development. The Apriori analysis produced a set of highly associated rules, all of which consistently pointed to age between 21 and 24 as the dominant outcome. The strongest rule showed perfect confidence of 1.0 when combining demographic attributes of those who report the most positive PBL experiences within the age range. Overall, this study provides strong empirical evidence that PBL significantly enhances teamwork skills by promoting active communication, collaborative problem-solving, and deeper understanding of statistical concepts. The findings contribute to curriculum design, teaching innovation, and policy enhancement in business and management education, highlighting PBL as an effective pedagogical strategy for strengthening teamwork competencies in preparation for the demands of contemporary workplaces.

* Corresponding author. E-mail address: rochin@uitm.edu.my
https://doi.org/10.24191/smrj.v22i2 September.9861

INTRODUCTION

The rapid evolution of contemporary workplaces has increased the demand for graduates who possess not only technical proficiency but also essential 21st century competencies, particularly teamwork, collaboration and problem-solving capabilities (Tight, 2021). Problem-Based Learning (PBL) has become one of the most widely adopted pedagogical approaches in higher education, particularly in disciplines that require analytical reasoning, collaboration and applied problem solving (Loyens et al., 2023). In statistics education, where students often struggle to connect abstract concepts with real world decision making, PBL provides an authentic learning environment that encourages active inquiry, teamwork, and the practical application of knowledge (Anchunda & Kaewurai, 2025). As universities place greater emphasis on industry aligned competencies, teamwork skills have emerged as a critical learning outcome, reflecting the collaborative nature of modern data-driven workplaces. However, understanding how students perceive, comprehend, and translate statistical concepts into meaningful team-based problem solving remains a constant challenge for educators. Based on the understanding that teamwork capability is a critical requirement in contemporary workplaces, this study explores the mechanisms through which PBL can provide the instructional framework for nurturing these essential competencies. The motivation of this study is driven by the widening gap in these critical skills between traditional instructional practices and the evolving expectations of industry, where collaborative problem-solving, data-driven knowledge discovery and integrated approach engagement are becoming essential (Xing et al., 2023). As such, education institutions require scientifically proven instructional strategies that foster deep understanding and applicable professional abilities (Alam & Mohanty, 2023). This study highlights the PBL as a potential solution and empirically evaluates its effectiveness.

PBL locate learners in complex, open-ended problems that require iterative reasoning, analytical thinking and collaborative inquiry (Yang et al., 2023). Through these processes, students will negotiate meaning, co-construct understanding and apply disciplinary knowledge in a manner that mirrors professional practice. Numerous studies have highlighted PBL's potential to foster critical thinking, conceptual understanding and communication skills as stated by Wardani and Fiorintina (2023), however, its influence on teamwork development particularly within statistic education remains lacking (Crespí et al., 2022). While collaboration is implicitly embedded in PBL tasks, the extent to which students perceive, internalise and operationalise teamwork behaviours during statistical problem-solving activities is not always well understood (Rojas et al., 2022).

Moreover, the integration of educational data mining (EDM) techniques into teaching and learning research as mentioned by Raut and Hajare (2025) has created new opportunities to empirically examine how students' perceptions, motivation, communication patterns and engagement related to the development of teamwork competencies. Recent educational research highlights the need to move beyond traditional assessments by using data-driven techniques to capture nuanced patterns of engagement and skill development (Sajja et al., 2025). Techniques such as cluster analysis and association rule mining provide deeper insights into how different groups of students interact with PBL tasks as reported by Yue et al. (2025), how they internalise statistical concepts and how these processes shape their teamwork capabilities. By analysing student responses through these methods, educators can discover hidden learning behaviours, dominant patterns of collaboration, and factors that influence the development of teamwork skills. This study investigates the classification of PBL experiences in relation to students' teamwork skills, focusing on their perceptions, understanding and application of statistical concepts.

LITERATURE REVIEW

Problem-Based Learning (PBL) has been widely recognised as an instructional approach that promotes active cognitive engagement, self-directed learning and practical problem solving (Huang et al., 2023).

https://doi.org/10.24191/smrj.v22i2 September.9861

Based on constructivist learning theory, PBL positions students at the centre of the learning process by encouraging students to collaborate as mentioned by Wang et al. (2023), negotiate and apply disciplinary knowledge to real world scenarios. In the context of quantitative subjects as statistics, several studies highlight that PBL helps students shift from memorisation toward conceptual understanding and higher order reasoning (Lu et al., 2021). Research consistently shows that PBL environments develop better memory of statistical concepts, improved analytical thinking and stronger confidence in applying statistical methods to practical problems (Lu, 2023).

According to Prada et al. (2022), teamwork skills, a core outcome of PBL, have become increasingly important in higher education, especially as employers demand graduates who can work effectively in dynamic and multidisciplinary teams. The literature identifies teamwork as a multidimensional competence encompassing communication, coordination, conflict resolution, and shared decision making (Boelt, 2023). Studies demonstrate that PBL naturally supports these skills by requiring students to engage in cooperative tasks, distribute responsibilities and collectively evaluate solutions (Casquero-Modrego et al., 2022). Effective teamwork within PBL does not only enhance academic performance but also prepares students for collaborative challenges in professional environments particularly those involving data interpretation, evidence-based reasoning and statistical analysis.

The role of perception and understanding in shaping teamwork outcomes has been a focal point in recent educational research. Students' perceptions of PBL activities such as perceived relevance, clarity of tasks and group interactions strongly influence their motivation and engagement (Boelt, 2023). Zheng et al. (2023) agreed that positive perceptions have been found to correlated with deeper learning strategies and more consistent team performance. Similarly, students' understanding and application of statistical concepts determine how they contribute to group discussions, problem framing, and solution development (Santos-Trigo, 2024). When students possess a solid conceptual foundation, they are more capable of participating in meaningful collaborative reasoning, thus strengthening overall teamwork quality.

With the growing availability of educational data, data mining techniques have become increasingly valuable in examining student behaviours, learning patterns and performance outcomes. Cluster analysis such as K-means, enables the classification of students based on shared characteristics or behavioural traits offering hidden knowledge that traditional evaluations may overlook (Pansri et al., 2024). Likewise, association rule mining, particularly the Apriori algorithm, has been used to uncover hidden relationships between learning behaviours and competency development (Hao et al., 2023). Prior studies have applied these techniques to identify patterns in student engagement, predict academic success and analyse the effectiveness of teaching and learning interventions. However, limited research has focused on using such techniques to evaluate the interplay between PBL, teamwork skills and statistical learning in a single integrated framework.

Therefore, existing literature highlight the need for deeper analytic approaches to understand how learners experience PBL and how these experiences translate into teamwork development. This study extends previous work by employing data-driven techniques to examine student perceptions, understanding and application of statistical concepts within PBL environments. By integrating cluster analysis, classification machine learning algorithms and association rule mining, this study provides a comprehensive empirical perspective on how PBL enhances teamwork competencies, filling a notable gap in both PBL and statistics education research.

https://doi.org/10.24191/smrj.v22i2 September.9861

METHODOLOGY

Research Design

This study employed a quantitative research design supported by educational data mining techniques to examine how Problem-Based Learning (PBL) contributes to the development of teamwork skills through students' perceptions, understanding and application of statistical concepts. A structured questionnaire consisting of 20 attributes and one target class (teamwork skills) was administered to undergraduate students enrolled in statistics related project course. The dataset comprised 102 valid responses, each measured using a nominal Likert type scale ranging from moderated to very high development. The attributes captured multiple dimensions of the learning experience, including students' perception of PBL suitability, interest level, commitment, motivation, conceptual understanding, material usage, lecturer guidance, communication, collaboration, and interpersonal competencies.

Data Description

Data were collected form servicing code application records submitted by various faculties to the Faculty of Business and Management for the academic session. Each record represents a single course request and contains the following information as depicted in the Table 1.

Table 1. Dataset description

No	Attribute	Data type
1	Age	Nominal
2	Gender	
3	Year of Study	
4	Faculty	
5	I prefer the project to a totally traditional course (theory/exercises solved by the lecturer)	Likert Scale: 1 – Very Low 2 – Low 3 – Moderate 4 – High 5 – Very High
6	I consider Problem-Based Learning to be a suitable methodology for my training in statistics	
7	The project has increased my interest in the course	
8	The time invested in the project was worth it	
9	I have fully committed to the project	
10	I am very proud of the work done	
11	The realisation of the project has increased my motivation towards the course	
12	The project has helped me to better assimilate the concepts and content of the course when preparing for the exam	
13	I have used the material prepared by my classmates (videos) to prepare for the exam	
14	Once the project was completed, my perception of the subject has changed	
15	The lecturer's indications on how to approach the tasks were sufficient	
16	The project has helped me to express myself rigorously using the appropriate statistical language	
17	The project has helped me to develop my interpersonal skills with my colleagues	
18	There has been smooth collaboration and communication throughout the project with my colleagues	
19	There has been fluid collaboration and communication with the lecturer throughout the project	
20	The project has helped me to develop my teamwork skills (Class)	

Data Preprocessing

Prior to analysis, the dataset was pre-processed in the WEKA 3.9 Explorer environment. All responses were examined for consistency, missing values and appropriate scale distribution. Due to the categorical nature of the dataset, no numerical normalisation was required.

Analytical Techniques and Validation

The analysis procedure was structured into three phases. The first phase involved descriptive and visual analytics using WEKA's built in visualisation tools to identify patterns and trends in student responses. Bar charts for all variables were generated with colour coded categories representing moderate (blue), high (red)

https://doi.org/10.24191/smrj.v22i2 September.9861

and very high (turquoise) levels of teamwork related development, enabling a holistic view of learning outcomes across the cohort.

In the second phase, EM clustering was applied to uncover natural groupings among student responses and to explore how different combinations of perceptions, motivations and communication attributes aligned with varying levels of teamwork skills. Clusters were evaluated based on cluster centroids, attribute dominance and within cluster patterns to provide insight into student profiles and behavioural tendencies in the PBL environment.

Third phase involved predictive modelling using the classification model in WEKA focusing on the rules-based algorithms namely PART, JRip, Decision Table, OneR and ZeroR. The 'use training set' test option was selected to assess the classifiers' ability to identify relationships within the actual data distribution. Model performance was evaluated through standard classification metrics including accuracy, precision, recall, F-measure, and ROC Area. The PART algorithm emerged as the best performing classifier demonstrating its capability to extract interpretable rules that accurately represent the complex interplay between PBL activities and teamwork skill development.

Additionally, association rule mining using the Apriori algorithm was used to identify co-occurrence patterns between student perceptions and teamwork skills. Minimum support and confidence thresholds were set iteratively to ensure meaningful and pedagogically relevant rules. These rules provided deeper insight into which aspects of PBL such as communication with peers, lecturer guidance and commitment were most frequently associated with higher levels of teamwork development.

Overall, the methodology framework integrates statistical analysis, clustering, classification and association mining to provide a comprehensive understanding of how students' learning experiences within a PBL context translate into teamwork skill formation. The use of multiple analytical techniques is ensured within contemporary educational data mining practices.

RESULTS AND FINDINGS

The analysis main objective is to identify the trends of teamwork skills engagement and development based on perception, understanding and application of statistical concepts. Several machine learning techniques, namely clustering, classification and attribute selection were applied to the teamwork skills development dataset and analysed using WEKA software.

Visualise All

To complement the statistical modelling and association analysis, this study utilised WEKA's attribute visualisation tool to explore hose student's responses across all variables align with their reported teamwork skill development levels. As shown in Figure 1, the visualisation adopts a colour coded scheme where blue representing moderate, red representing high and turquoise representing very high teamwork development. This categorisation allows visually inspect how demographic factors and perceptions of the PBL experience cluster around different level so teamwork outcomes. Visual analysis plays a crucial role in educational data mining as it allows us to detect intuitive patterns, highlighting behavioural consistencies and validate algorithms results through observable trends.

https://doi.org/10.24191/smrj.v22i2 September.9861

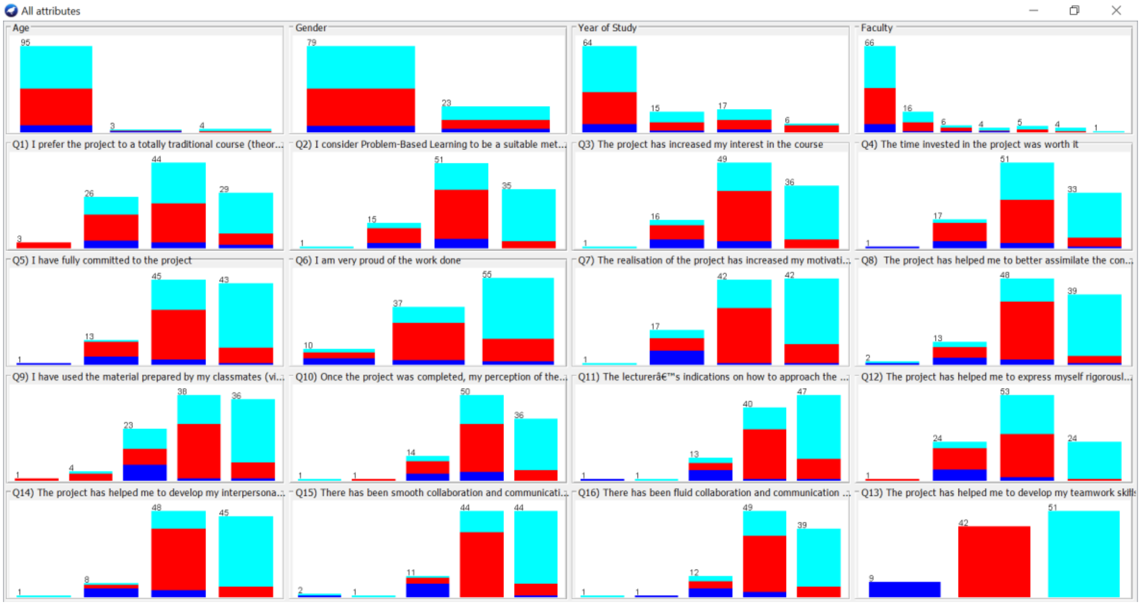

Fig. 1. Visualize all attributes showing patterns of teamwork skills engagement or development

Across cognitive, motivational, behavioural and communication related attributes, the responses were predominantly clustered in the high and very high categories, indicating that students who perceived PBL activities favourably also demonstrated stronger teamwork skills. Moderate responses were minimal suggesting uniformly positive engagement with the collaborative learning environment. Demographic trends particularly among students aged 21 to 24, females and those in Year 2 reflected the high teamwork clusters. Overall, the visual trends reinforce the conclusion that PBL effectively enhances teamwork competencies with consistent patterns across both demographic and pedagogical variables (Jiang et al., 2023).

Strong Concentration of High and Very High Teamwork Development Across Most Attributes (Red and Turqoise)

Across most attributes including interest (Q3), commitment (Q5), motivation (Q7), concept comprehension (Q8), communication (Q15) and teamwork (Q13), the distribution is heavily skewed toward red (high) and turquoise (very high). This indicates that students who perceived BPL activities positively also tended to report stronger teamwork abilities. This pattern supports the argument that PBL encourages active participation, shared responsibility and collaborative problem solving, aligning with well-established pedagogical theories in constructive and experiential learning (Al-Thani & Ahmad, 2025).

Minimal Moderate Level of Teamwork Development (Blue)

The blue bars depicted the moderate teamwork development appear only sparsely often representing fewer than three responses per item. This suggests that few students experienced only moderate benefits and most students gained substantially from the group-based statistical project. PBL facilitated consistently strong team interaction across diverse student backgrounds. This validates the study’s early findings from classification models, where PBL related attributes consistently ranked high in predicting teamwork outcomes (Huang, 2022).

https://doi.org/10.24191/smrj.v22i2 September.9861

Expectation Maximisation Clustering: Exploratory Analysis

We performed model-based clustering using the EM algorithm in WEKA on the full dataset of 102 instances with 20 attributes as shown in Table 2. Cross validation selected four clusters, and the model partitioned the sample into groups of 46 (45%). 10 (10%), 36 (35%) and 10 (10%) instances. The log-likelihood for the fitted solution was -15.38793.

Table 2. Summary of EM Clustering Results

Cluster	Instances Percentage	Total Instances	Teamwork Skills	Engagement Type
Cluster 0	45%	46	Moderate	Respond positively to PBL but would benefit from reinforcement to reach the highest levels of teamwork performance
Cluster 1	10%	10	Low	Less convinced of PBL's suitability or less engaged in collaborative behaviours.
Cluster 2	35%	36	High	Project increased interest, motivation and help assimilate concepts indicating high cognitive engagement and positive perception of PBL
Cluster 3	10%	10	High	

Cluster Profiles and Interpretation

Inspection of attribute distributions shows distinct behavioural and personality traits.

High Engagement and Teamwork clusters: Cluster 2 and Cluster 3

These clusters are characterised by strong positive responses to the teamwork item (Q13) and to many PBL-related items such as Q2 – Q8, Q11 and Q12. A large proportion of these respondents reported that the project increased interest, motivation and help assimilate concepts indicating high cognitive engagement and positive perception of PBL. These groups likely represent students who both understand and apply statistical concepts within collaborative contexts and therefore derive the greatest teamwork benefit from PBL (Chang et al., 2022).

Moderate Engagement and Consistent Positivity Teamwork cluster: Cluster 0

The largest cluster with 46 instances generally reports agreement with mostly 4 on Likert scale with teamwork and PBL benefits items. Respondents show moderate to strong engagement and use of peer materials (Q9), but not as consistently strong as cluster 2 and 3. This cluster may represent most students who respond positively to PBL but would benefit from reinforcement to reach the highest levels of teamwork performance. These learners appear disengaged, less responsive to PBL and more likely to struggle with group-based tasks. They may require alternative instructional approaches or additional lecturer guidance (Maimaiti et al., 2023).

Low Engagement and Low Teamwork cluster: Cluster 1

The smallest cluster with 10 instances shows relatively lower or more neutral responses with more 3s Likert scale on key items including the teamwork item. This group appears less convinced of PBL's suitability or less engaged in collaborative behaviours. They may need additional reinforcement, clearer lecture guidance, or modified task design to convert neutral perceptions into active collaborative performance (Hanshaw & Sullivan, 2025).

https://doi.org/10.24191/smrj.v22i2 September.9861

Attribute Selection: Determinants of Teamwork skills (The Project has helped me to develop my teamwork skills as class)

Attribute Selection using Information Gain Ranking identified the most influential factors contributing to teamwork skills development variation. Figure 2, Table 3 and Table 4 show the attribute importance ranking respectively.

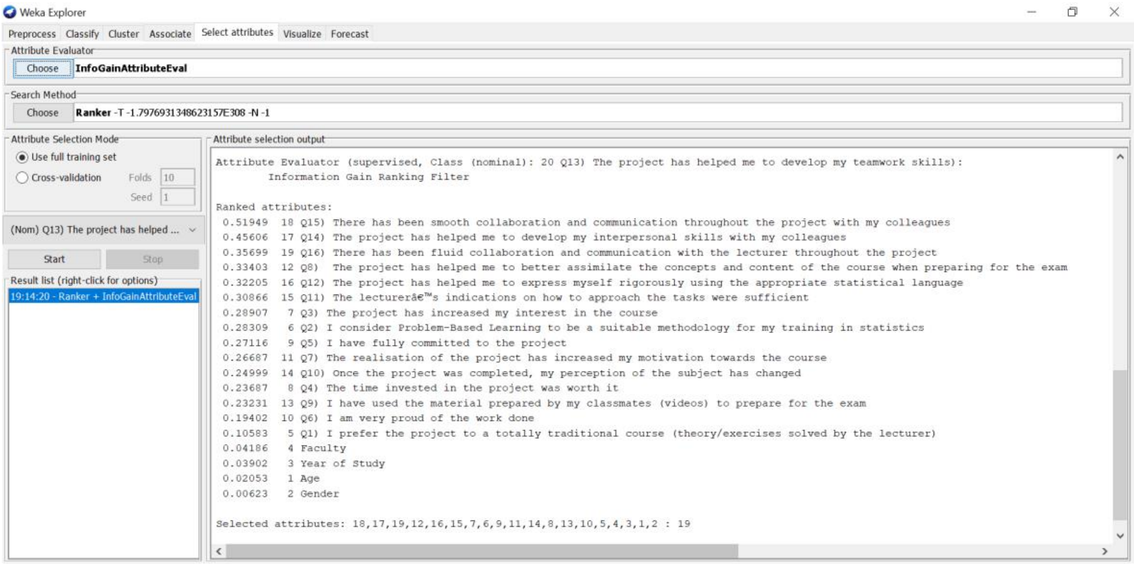

Fig. 2. Attribute ranking using Information Gain Attribute evaluation

Table 3. Attribute importance ranking

=== Attribute Selection on all input data ===

Search Method:
Attribute ranking.

Attribute Evaluator (supervised, Class (nominal): 20 Q13) The project has helped me to develop my teamwork skills):
Information Gain Ranking Filter

Ranked attributes:
0.51949 18 Q15) There has been smooth collaboration and communication throughout the project with my colleagues
0.45606 17 Q14) The project has helped me to develop my interpersonal skills with my colleagues
0.35699 19 Q16) There has been fluid collaboration and communication with the lecturer throughout the project
0.33403 12 Q8) The project has helped me to better assimilate the concepts and content of the course when preparing for the exam
0.32205 16 Q12) The project has helped me to express myself rigorously using the appropriate statistical language
0.30866 15 Q11) The lecturer’s indications on how to approach the tasks were sufficient
0.28907 7 Q3) The project has increased my interest in the course

https://doi.org/10.24191/smrj.v22i2 September.9861

```
 0.28309   6 Q2) I consider Problem-Based Learning to be a suitable methodology for my training in statistics
 0.27116   9 Q5) I have fully committed to the project
 0.26687  11 Q7) The realisation of the project has increased my motivation towards the course
 0.24999  14 Q10) Once the project was completed, my perception of the subject has changed
 0.23687   8 Q4) The time invested in the project was worth it
 0.23231  13 Q9) I have used the material prepared by my classmates (videos) to prepare for the exam
 0.19402  10 Q6) I am very proud of the work done
 0.10583   5 Q1) I prefer the project to a totally traditional course (theory/exercises solved by the lecturer)
 0.04186   4 Faculty
 0.03902   3 Year of Study
 0.02053   1 Age
 0.00623   2 Gender

Selected attributes: 18,17,19,12,16,15,7,6,9,11,14,8,13,10,5,4,3,1,2 : 19
```

Table 4. Ranking of attribute using information gain attribute evaluation

Rank	Attribute	Information Gain Value
1	18 Q15) There has been smooth collaboration and communication throughout the project with my colleagues	0.51949
2	Q14) The project has helped me to develop my interpersonal skills with my colleagues	0.45606
3	19 Q16) There has been fluid collaboration and communication with the lecturer throughout the project	0.35699
4	12 Q8) The project has helped me to better assimilate the concepts and content of the course when preparing for the exam	0.33403
5	16 Q12) The project has helped me to express myself rigorously using the appropriate statistical language	0.32205
6	15 Q11) The lecturer's indications on how to approach the tasks were sufficient	0.30866
7	7 Q3) The project has increased my interest in the course	0.28907
8	6 Q2) I consider Problem-Based Learning to be a suitable methodology for my training in statistics	0.28309
9	9 Q5) I have fully committed to the project	0.27116
10	11 Q7) The realisation of the project has increased my motivation towards the course	0.26687
11	14 Q10) Once the project was completed, my perception of the subject has changed	0.24999
12	8 Q4) The time invested in the project was worth it	0.23687
13	13 Q9) I have used the material prepared by my classmates (videos) to prepare for the exam	0.23231
14	10 Q6) I am very proud of the work done	0.19402
15	5 Q1) I prefer the project to a totally traditional course (theory/exercises solved by the lecturer)	0.10583
16	4 Faculty	0.04186
17	3 Year of Study	0.03902
18	1 Age	0.02053
19	2 Gender	0.00623

This feature selection analysis using the information gain attribute evaluator combined with the ranker search method provides a clear picture of which variables contribute most to explaining the target attribute as class namely student's perceptions of whether the project helped them develop teamwork skills. Information gain measures the reduction in entropy produced by each attribute, effectively identifying which variables carry the strongest discriminative power relative to the class label. The ranked output shows a consistent pattern which items directly reflecting collaboration, communication and interpersonal development dominate the top of the list. This aligns logically with the nature of the outcome variable, as teamwork related perceptions are more strongly shaped by students' social and collaborative experiences during the project (Jiang et al., 2023).

https://doi.org/10.24191/smrj.v22i2 September.9861

Attribute Q15 (smooth collaboration and communication throughout the project with my colleagues) and Q14 (helped me develop my interpersonal skills with my colleagues) emerge as the highest ranked predictors, reinforcing the expected theoretical coherence between teamwork development and interpersonal interaction. Their high Information Gain values indicate that student's teamwork evaluations are largely influenced by how effectively they engaged with peers, which is consistent with established literature on collaborative learning and project-based pedagogy (Adesina et al., 2023). Similarly, Q16 (communication with the lecturer), Q8 (assimilation of course concepts) and Q12 (ability to express oneself using appropriate statistical language) appear among the top features, suggesting that teamwork growth is not only tied to peer collaboration but also shaped by the academic environment surrounding the project. This highlights a more holistic perspective where teamwork development is embedded in a broader learning dynamic including clarity of instruction and deep understanding within a structured curriculum (James et al., 2022).

Mid ranked attributes such as Q11 (clarity of lecturer instructions), Q3 (interest in the course), Q2 (suitability of PBL) and Q5 (commitment to the project) suggest secondary but meaningful contributions. These factors appear to act as supportive conditions for students who are more engaged, motivated and guided also tend to report better teamwork outcomes. Meanwhile, attributes related to post project reflection, for example Q7 and Q10, show moderate relevance, implying that changes in motivation or perception after completing the task contribute to understanding teamwork but do not serve as primary determinants (Rodríguez-Sabiote et al., 2022).

Demographic variables such as faculty, year of study, age and gender, appear near the bottom of the ranking with negligible information gain scores. This finding is not only statistically expected but pedagogically meaningful, indicating that teamwork development is shaped more by learning experience and project structure rather than inherent personal characteristics. Such a result supports the idea that well designed collaborative learning activities can benefit diverse student groups without bias across demographic categories.

Overall, the ranking outcomes present a logically reasonable and empirically observable trend. Variables most closely aligned with collaborative behaviour and interpersonal engagement display the strongest predictive capacity, while demographic factors show minimal influence. This strengthens the validity of the evaluation instrument and highlights the effectiveness of feature selection in isolating pedagogically relevant attributes. The findings justify the subsequent analytical steps such as clustering or classification by ensuring that the most informative and conceptually coherent features are retained leasing to more robust and interpretable modelling outcomes.

Apriori Association Rule Mining Result

Apriori is one of the most widely used methods for uncovering meaningful co-occurrence patterns within categorical datasets. Unlike classification and clustering methods that focus on prediction or grouping, Apriori is designed to identify frequent item sets and generate if-then rules that explain how attributes tend to appear together. This makes Apriori particularly suitable for educational datasets, where patterns in demographic traits, perception ratings and course-related behaviours uncover hidden patterns. As shown in Table 5, the Apriori analysis revealed that a consistent and dominant pattern in which most strong association rules converged on a single outcome variable where Age within 21 to 24.

https://doi.org/10.24191/smrj.v22i2 September.9861

Table 5. Apriori association rule mining result

```
Apriori
=======

Minimum support: 0.45 (46 instances)
Minimum metric <confidence>: 0.9
Number of cycles performed: 11

Generated sets of large itemsets:

Size of set of large itemsets L(1): 15

Size of set of large itemsets L(2): 14

Size of set of large itemsets L(3): 2

Best rules found:

 1. Gender=Female Year of Study=Year 2 56 ==> Age=21-24 56    <conf:(1)> lift:(1.07) lev:(0.04) [3] conv:(3.84)
 2. Gender=Female Faculty =Business and management 56 ==> Age=21-24 56    <conf:(1)> lift:(1.07) lev:(0.04) [3] conv:(3.84)
 3. Q16) There has been fluid collaboration and communication with the lecturer throughout the project=4 49 ==> Age=21-24 49    <conf:(1)> lift:(1.07) lev:(0.03) [3] conv:(3.36)
 4. Gender=Female 79 ==> Age=21-24 78    <conf:(0.99)> lift:(1.06) lev:(0.04) [4] conv:(2.71)
 5. Year of Study=Year 2 64 ==> Age=21-24 63    <conf:(0.98)> lift:(1.06) lev:(0.03) [3] conv:(2.2)
 6. Faculty =Business and management 66 ==> Age=21-24 64    <conf:(0.97)> lift:(1.04) lev:(0.02) [2] conv:(1.51)
 7. Q2) I consider Problem-Based Learning to be a suitable methodology for my training in statistics=4 51 ==> Age=21-24 49    <conf:(0.96)> lift:(1.03) lev:(0.01) [1] conv:(1.17)
 8. Q14) The project has helped me to develop my interpersonal skills with my colleagues=4 48 ==> Age=21-24 46    <conf:(0.96)> lift:(1.03) lev:(0.01) [1] conv:(1.1)
 9. Q10) Once the project was completed, my perception of the subject has changed=4 50 ==> Age=21-24 47    <conf:(0.94)> lift:(1.01) lev:(0) [0] conv:(0.86)
10. Q12) The project has helped me to express myself rigorously using the appropriate statistical language=4 53 ==> Age=21-24 49    <conf:(0.92)> lift:(0.99) lev:(-0) [0] conv:(0.73)
```

With minimum support set at 0.45 and minimum confidence at 0.90, the algorithm generated highly reliable rules, indicating that more than 45 % of the dataset supported each association. Across the top rules, gender, year of study, faculty and several pedagogical perception variables repeatedly co-occurred with the 21 to 24 age group. For instance, the strongest rules such as gender equal to female, and Year 2 will resulting to age 21 to 24 with confidence equal to 1 while gender equal to female and faculty equal to business and management will also resulting to age 21 to 24 with confidence equal to 1 showing that combination of demographic factors perfectly predict membership in this age category. These highly confident rules are expected given the typical age distribution of second year undergraduate students in Malaysian higher education, thus reinforcing the interval validity of the dataset.

Interestingly, several PBL related attributes also co-appeared with Age equal to 21 to 24 such as students reporting fluid communication with the lecturer, perceiving PBL as a suitable methodology, developing interpersonal skills and experiencing a positive change in subject perception. Although these

https://doi.org/10.24191/smrj.v22i2 September.9861

rules demonstrate slightly lower confidence with 0.92 to 0.96, they still indicate strong patterns suggesting that students who rated PBL experiences positively tend to fall within this age group. This trend may reflect development maturity, as student aged 21 to 24 are typically at a stage where collaborative learning, peer communication and active engagement with lecturers align more comfortably with their learning preferences a cognitive readiness. From a pedagogical perspective, this support the notion that PBL has its strongest impacts and perceived value among mid programme undergraduates, who have already developed foundational learning skills and are more receptive to active learning methodologies (Chen et al., 2023).

However, the lift values across all rules remain close to 1, indicating that while the associations are highly confident, they do not represent unexpected or non-random relationships rather they reflect patterns strongly driven by the sample's demographic composition. This is not a limitation but a meaningful insight into the Apriori results confirm that positive PBL outcomes particularly related communication, interpersonal development, and lecturer interaction are not randomly distributed but are concentrated among the age group most represented in the dataset. The consistency of these patterns indicates a stable student profile in which younger adult learners appear to benefit most clearly from PBL structures, further supporting existing literature that links PBL effectiveness with learners who possess adequate independence, motivation and adaptability (Ni'mah et al., 2024).

Overall, the Apriori findings validate the dataset structure, highlighting demographic dominance in rule formation, and demonstrating that students who perceive PBL positively tend overwhelmingly to be within the typical 21-to-24-year age range, reinforcing the alignment between teaching approach and learner readiness. These hidden knowledges serve as meaningful foundation for interpreting clustering and classification results within the broader context of PBL's role in developing teamwork and communication skills.

Classification Algorithms

The classification analysis conducted using WEKA's rules-based algorithms demonstrates that the PART classifier offers the most accurate and reliable predictive performance compared to the other algorithms tested as shown in Table 6.

Table 6. Classification accuracy based on rules group

Model	Accuracy	Precision	Recall	ROC Area
Decision Table	79.4118 %	0.811	0.794	0.894
JRip	82.3529 %	0.836	0.824	0.883
OneR	77.451 %	0.782	0.775	0.808
PART	86.2745 %	0.872	0.863	0.902
ZeroR	50 %	?	0.500	0.500

Using the training evaluation method, PART achieved a classification accuracy of 86.27% outperforming the Decision Table (79.14%), JRip (82.35%), OneR (77.45%) and ZeroR (50%) classifiers. The superior performance of PART is further supported by its balanced evaluation metrics including high precision of 0.872, recall of 0.863, F-measure of 0.863, and a robust ROC Area of 0.902, indicating strong discriminative ability across the target classes.

The detailed accuracy by class reveals that PART maintains a consistently high true positive rate (TP rate) and low positive rate (FP rate), particularly for the dominant classes. For example, the classifier achieved TP rates of 0.889 and 0.929 for two of the major classes, reflecting its capacity to capture subtle distinctions between student responses as shown in Figure 3. The Matthews Correlation Coefficient (MCC) values ranging between 0.752 and 0.878 further validate the strength of the model as MCC is a more robust

https://doi.org/10.24191/smrj.v22i2 September.9861

indicator for classification performance, particularly when classes are imbalanced. This is crucial in educational datasets, where distribution across Likert scale categories is rarely uniform.

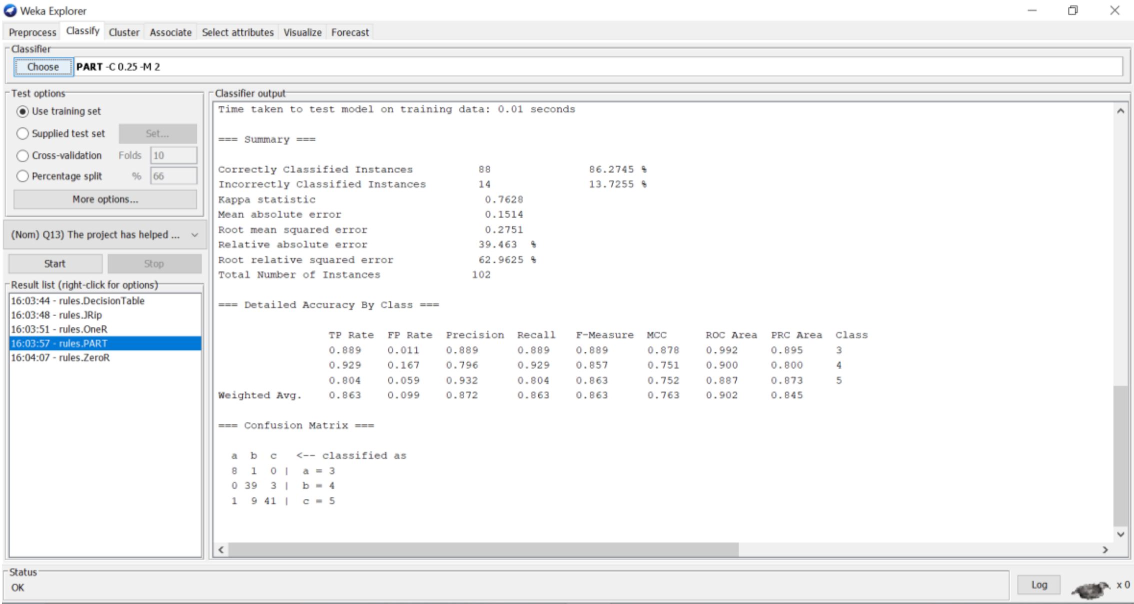

Fig. 3. Classification result using PART algorithm that generate highest accuracy compared to other model in rules group of classification

In contrast, ZeroR produced the lowest performance, with an accuracy of only 50% since it predicts solely based on the majority class. Its evaluation metrics for precision, MCC and F-measure are denoted with '?' for most classes except for class label 5 (Very high) indicating an inability to meaningfully distinguish between categories in an imbalanced dataset. This emphasis the inadequacy of majority class baselines in studies involving pedagogical such as teamwork development, perception, and conceptual handling.

Decision Table and OneR both simplified rule learners, recorded weaker performance due to their limited capacity to model complex interactions among variables. OneR for instance, relies on a single attribute which restricts its predictive depth, explaining its lower accuracy of 77.45%. JRip performed moderately well (82.35%), but its rule generalisation appears less effective than PART's incremental rule partitioning strategy, which tends to create more refined and accurate decision structures.

Overall, these findings highlight the suitability of PART algorithm for educational data mining applications where student responses exhibit overlapping behavioural patterns and multiple influencing factors. PART's hybrid approach combining decision tree partitioning with rule extraction allows it to handle interactions between perception, teamwork skills, and application of statistical concepts more effectively than simpler rule learners. The strong performance of PART therefore provides a reliable basis for interpretating student learning patterns within the Problem-Based Learning environment, supporting its use in modelling and predicting educational outcomes in similar pedagogical studies.

DISCUSSION

The findings of this study provide strong empirical evidence supporting the effectiveness of Problem-Based Learning (PBL) in promoting teamwork development and enhancing students' engagement with statistical

https://doi.org/10.24191/smrj.v22i2 September.9861

concepts. Across the analysis of EM clustering, Apriori association rules and classification modelling, the patterns consistently show that students who reported higher levels of conceptual understanding, motivation and communication with the lecturer also demonstrated stronger teamwork skills. This alignment strengthens established historical arguments in the theory of knowledge construction that meaningful learning occurs through active participation, collaboration, and the integration of new knowledge with prior understanding (Li et al., 2023).

The clustering results revealed three distinct learner profiles, with the largest cluster representing students who demonstrated very high teamwork development alongside strong perceptions of PBL's relevance, improved motivation, and enhanced understanding. This suggests that the PBL environment successfully created a context where students could collectively construct meaning, negotiate problem solutions, and apply statistical reasoning in a socially interactive manner. These findings align with Schneider et al. (2022), where perspectives, which suggest that learning is optimized when cognitive tasks are mediated through social interaction and guided support. Similarly, the strong clustering around communication related attributes highlights the importance of collaborative problem-solving.

The Apriori analysis further reinforced these dynamics by highlighting that teamwork related attributes frequently co-occurred with factors such as enhanced interpersonal skills, improved statistical language use, and positive shifts in perception toward the subject. These rules indicate that teamwork does not develop in isolation instead it emerges as an integrated outcome of multiple evidence factors within the PBL environment. When students experience meaningful lecturer guidance, smooth communication and opportunities for self-expression using appropriate statistical terminology, they are more likely to internalize collaborative competencies. The strong confidence values observed in the rules suggest that teamwork development is highly predictable within this learning context, demonstrating the robustness of PBL as a pedagogical intervention for fostering collaborative learning (Oanh & Dang, 2025).

The classification results provide additional support for these findings. The PART rule-based classifier achieved the highest accuracy outperforming Decision Table, OneR, JRip and ZeroR. This indicates that teamwork development is best understood through multi-attribute rule-based structures rather than simple linear models. The high precision and recall achieved for most classes further confirm that teamwork development is influenced by a logically consistent set of learner attributes, which can be predictable. The poor performance of ZeroR marked by imbalanced predictions and limited discriminatory power, highlights the multidimensional nature of teamwork and the inadequacy of single class baselines in explaining it. These results collectively confirm that teamwork skills in a PBL context emerge from a complex interaction of cognitive, behavioural and attitudinal variables (Wang et al., 2023).

THEORETICAL AND PRACTICAL IMPLICATIONS

Theoretical Implications

The consistent association between collaboration, motivation, lecturer guidance and teamwork strengthens the theoretical position that learning is fundamentally social. The results provide empirical evidence for models where knowledge construction is shaped by shared problem solving, reflective dialogue and group interaction. While PBL is well-established in medical and engineering fields, its theoretical impact on statistics education needs to be explored and further research. This study expands the theoretical discussion by demonstrating how PBL improves not only conceptual understanding but also teamwork competencies that are often overlooked in quantitative education research. Moreover, the successful application of clustering, association and classification techniques validates the use of EDM to uncover unseen behavioural patterns in learning environments. This study demonstrates how analytics can enhance theoretical understanding of student learning processes beyond traditional self-report or descriptive approaches.

https://doi.org/10.24191/smrj.v22i2 September.9861

Practical Implications

The results highlight the need for instructors to intentionally embed structured collaboration, communication impact and reflective tasks within PBL activities to maximize teamwork outcomes. Attributes related to lecturer guidance and communication were strong predictors of teamwork development. This highlights the importance of timely feedback, clear expectations and supportive facilitation in shaping student collaboration. Cluster profiles provide a data-driven framework for identifying students who may require additional support in motivation, conceptual understanding or collaborative engagement. Educators can use this hidden knowledge to personalize interventions and enhance learning equity. This study illustrates how EDM technique can be embedded into teaching practice to continuously monitor teamwork development and refine PBL implementation based on real-time evidence.

In summary, the analysis demonstrates that PBL is powerful pedagogical strategy for developing teamwork skills in statistic courses. The findings justify the continued integration of PBL into quantitative programmes and emphasize that collaborative learning improves when students are supported through clear guidance, meaningful engagement and opportunities to apply knowledge to real-world problems. The combination of results across multiple analytic techniques strengthens the reliability of the conclusions and provides a comprehension foundation for pedagogical improvement and future research.

CONCLUSION

This study provides strong empirical evidence that Problem-Based Learning (PBL) is an effective pedagogical approach for enhancing teamwork development and strengthening students' engagement with statistical concepts. Through the integration of clustering, association rule mining, and classification modelling, the analysis offers a multidimensional understanding of how students perceive, internalize and apply statistics within a collaborative learning environment. The results consistently demonstrate that students who experience higher motivation, positive perception shifts, stronger lecturer-student communication and greater conceptual clarity also exhibit significantly higher levels of teamwork skills. Clustering is exploratory and descriptive that uncovers patterns but does not indicate causality. The sample size is modest with only 102 instances, and the dataset reflects self-report measure. For future work it should validate cluster membership with longitudinal or performance data, conduct supervised modelling to predict cluster assignment, and test targeted instructional interventions to move students from neutral or moderate clusters to high teamwork profile. These patterns support the idea that PBL creates a learning environment where cognitive understanding and collaborative competence are mutually beneficial for both students and academicians.

The high accuracy achieved by the PART classifier further confirms that teamwork development is influenced by interconnected behavioural, attitudinal and cognitive attributes rather than by singular or isolated factors. The Apriori rules strengthen this finding by revealing stable and interpretable associations between teamwork development and communication, interpersonal skills and positive engagement with the learning process. This hidden knowledge collectively highlights the value of embedding structured collaborative tasks, guided facilitation and real-world statistical problem scenarios into the curriculum.

Overall, the study concludes that PBL offers a robust framework for integrating knowledge from specific disciplines and essential soft skills such as communication, interpersonal collaboration and teamwork competencies that are critical for academic success and professional readiness. By demonstrating the effectiveness of PBL through data-driven evidence-based, this study contributes to ongoing efforts to modernize statistics education and alignment with global shifts toward active, collaborative and learner centred pedagogies. Future work may extend these findings by examining longitudinal impacts, exploring

https://doi.org/10.24191/smrj.v22i2 September.9861

cross disciplinary contexts or integrating adaptive learning analytics to support personalized interventions within PBL environments.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the support provided by Faculty of Business and Management, Universiti Teknologi MARA in facilitating the publication of this article. Appreciation is also extended to all respondents for their valuable contributions during the data collection process. The authors further express sincere thanks to the reviewers for their constructive and insightful feedback.

CONFLICT OF INTEREST STATEMENT

Authors declare that there is no conflict of interest regarding the publication of the paper.

AUTHORS CONTRIBUTIONS

Authors acknowledge their contribution to the paper as follows: study conception and design, analysis and interpretation: Nur Atiqah Rochin Demong, data collection and draft manuscript preparation: Masrur Mohd Khir. All authors reviewed and approved the final version of the manuscript.

REFERENCES

Adesina, O. O., Adesina, O. A., Adelopo, I., & Afrifa, G. A. (2023). Managing group work: the impact of peer assessment on student engagement. *Accounting Education*, *32*(1), 90–113. https://doi.org/10.1080/09639284.2022.2034023

Al-Thani, N. J., & Ahmad, Z. (2025). Driving project-based learning and problem-based learning through research in middle schools. In *Teaching and learning with research cognitive theory*. Springer. https://doi.org/10.1007/978-3-031-87544-1_3

Alam, A., & Mohanty, A. (2023). Cultural beliefs and equity in educational institutions: exploring the social and philosophical notions of ability groupings in teaching and learning of mathematics. *International Journal of Adolescence and Youth*, *28*(1), 2270662. https://doi.org/10.1080/02673843.2023.2270662

Anchunda, H. Y., & Kaewurai, W. (2025). An instructional model development based on inquiry-based and problem-based approaches to enhance prospective teachers' teamwork and collaborative problem-solving competence. *Social Sciences & Humanities Open*, *11*, 101480. https://doi.org/10.1016/j.ssaho.2025.101480

Boelt, A. M. (2023). Engineering students' development of PBL competences in a PBL curriculum: Exploring students' reflections of teamwork competences in PBL. Aalborg Universitetsforlag.

Casquero-Modrego, N., Núñez-Andrés, M. A., & Iniesto-Alba, M. J. (2022). Effects of small-group learning on the assessment of professional skills through a PBL activity. *Transactions in GIS*, *26*(4), 1735–1753. https://doi.org/10.1111/tgis.12897

Chang, T.-S., Wang, H.-C., Haynes, A. M., Song, M.-M., Lai, S.-Y., & Hsieh, S.-H. (2022). Enhancing student creativity through an interdisciplinary, project-oriented problem-based learning undergraduate curriculum. *Thinking Skills and Creativity*, *46*, 101173. https://doi.org/10.1016/j.tsc.2022.101173

Chen, J., Hasan, M. A., Du, X., & Kolmos, A. (2023). Exploring students' perception of the influence of PBL elements on the development of engineering identity. *IEEE Transactions on Education*, *66*(4), 393–403. https://doi.org/10.1109/TE.2023.3258548

https://doi.org/10.24191/smrj.v22i2 September.9861

Crespí, P., García-Ramos, J. M., & Queiruga-Dios, M. (2022). Project-based learning (PBL) and its impact on the development of interpersonal competences in higher education. *Journal of New Approaches in Educational Research*, *11*(2), 259–276. https://doi.org/10.7821/naer.2022.7.993

Hanshaw, G., & Sullivan, C. (2025). Exploring barriers to AI course assistant adoption: a mixed-methods study on student non-utilization. *Discover Artificial Intelligence*, *5*(1), 178. https://doi.org/10.1007/s44163-025-00312-x

Hao, Q., Choi, W. J., & Meng, J. (2023). A data mining-based analysis of cognitive intervention for college students' sports health using Apriori algorithm. *Soft Computing*, *27*(21), 16353–16371. https://doi.org/10.1007/s00500-023-09163

Huang, L., Li, X., Meng, Y., Lei, M., Niu, Y., Wang, S., & Li, R. (2023). The mediating effects of self-directed learning ability and critical thinking ability on the relationship between learning engagement and problem-solving ability among nursing students in Southern China: a cross-sectional study. *BMC nursing*, *22*(1), 212. https://doi.org/10.1186/s12912-023-01280-2

Huang, Y. (2022). Effectiveness of inquiry-based science laboratories for improving teamwork and problem-solving skills and attitudes. *Journal of Research in Science Teaching*, *59*(3), 329–357. https://doi.org/10.1002/tea.21729

James, M., Baptista, A. M. T., Barnabas, D., Sadza, A., Smith, S., Usmani, O., & John, C. (2022). Collaborative case-based learning with programmatic team-based assessment: A novel methodology for developing advanced skills in early-years medical students. *BMC Medical Education*, *22*(1), 81. https://doi.org/10.1186/s12909-022-03111-5

Jiang, D., Dahl, B., Chen, J., & Du, X. (2023). Engineering students' perception of learner agency development in an intercultural PBL (Problem-and Project-Based) team setting. *IEEE Transactions on Education*, *66*(6), 591–601. https://doi.org/10.1109/TE.2023.3273177

Li, R., Lund, A., & Nordsteien, A. (2023). The link between flipped and active learning: A scoping review. *Teaching in Higher Education*, *28*(8), 1993–2027. ttps://doi.org/10.1080/13562517.2021.1943655

Loyens, S. M., Van Meerten, J. E., Schaap, L., & Wijnia, L. (2023). Situating higher-order, critical, and critical-analytic thinking in problem-and project-based learning environments: A systematic review. *Educational Psychology Review*, *35*(2), 39. https://doi.org/10.1007/s10648-023-09757-x

Lu, H.-F. (2023). Statistical learning in sports education: A case study on improving quantitative analysis skills through project-based learning. *Journal of Hospitality, Leisure, Sport & Tourism Education*, *32*, 100417. https://doi.org/10.1016/j.jhlste.2023.100417

Lu, K., Pang, F., & Shadiev, R. (2021). Understanding the mediating effect of learning approach between learning factors and higher order thinking skills in collaborative inquiry-based learning. *Educational technology research and development*, *69*(5), 2475–2492. https://doi.org/10.1007/s11423-021-10025-4

Maimaiti, G., Jia, C., & Hew, K. F. (2023). Student disengagement in web-based videoconferencing supported online learning: an activity theory perspective. *Interactive Learning Environments*, *31*(8), 4883–4902. https://doi.org/10.1080/10494820.2021.1984949

Ni'mah, A., Arianti, E. S., Suyanto, S., Putera, S. H. P., & Nashrudin, A. (2024). Problem-Based Learning (PBL) methods within an independent curriculum (a literature review). *Sintaksis: Publikasi Para ahli Bahasa dan Sastra Inggris*, *2*(4), 165–174. https://doi.org/10.61132/sintaksis.v2i4.859

https://doi.org/10.24191/smrj.v22i2 September.9861

Oanh, D. T. K., & Dang, T. D. H. (2025). Effect of STEAM project-based learning on engineering students' 21st century skills. *European Journal of Educational Research*, *14*(3), 705–721. https://doi.org/10.12973/eu-jer.14.3.705

Pansri, B., Sharma, S., Timilsina, S., Choonhapong, W., Kurashige, K., Watanabe, S., & Sato, K. (2024). Understanding student learning behavior: Integrating the self-regulated learning approach and k-means clustering. *Education Sciences*, *14*(12). https://doi.org/10.3390/educsci14121291

Prada, E. D., Mareque, M., & Pino-Juste, M. (2022). Teamwork skills in higher education: is university training contributing to their mastery? *Psicologia: Reflexao e critica*, *35*, 5. https://doi.org/10.1186/s41155-022-00207-1

Raut, A., & Hajare, S. (2025, April 23–25). *Transforming education with data mining: opportunities, applications, and challenges*. 2025 International Conference on Inventive Computation Technologies (ICICT). [Conference presentation] Kirtipur, Nepal. https://doi.org/10.1109/ICICT64420.2025.11005098

Rodríguez-Sabiote, C., Olmedo-Moreno, E. M., & Expósito-López, J. (2022). The effects of teamwork on critical thinking: A serial mediation analysis of the influence of work skills and educational motivation in secondary school students. *Thinking Skills and Creativity*, *45*, 101063. https://doi.org/10.1016/j.tsc.2022.101063Get rights and content

Rojas, M., Nussbaum, M., Guerrero, O., Chiuminatto, P., Greiff, S., Del Rio, R., & Alvares, D. (2022). Integrating a collaboration script and group awareness to support group regulation and emotions towards collaborative problem solving. *International Journal of Computer-Supported Collaborative Learning*, *17*, 135–168. https://doi.org/10.1007/s11412-022-09362-0

Sajja, R., Sermet, Y., Cwiertny, D., & Demir, I. (2025). Integrating AI and learning analytics for data-driven pedagogical decisions and personalized interventions in education. In *Technology, knowledge and learning*. Springer. https://doi.org/10.1007/s10758-025-09897-9

Santos-Trigo, M. (2024). Problem solving in mathematics education: Tracing its foundations and current research-practice trends. *ZDM–Mathematics Education*, *56*(2), 211–222. https://doi.org/10.1007/s11858-024-01578-8

Schneider, S., Beege, M., Nebel, S., Schnaubert, L., & Rey, G. D. (2022). The cognitive-affective-social theory of learning in digital environments (CASTLE). *Educational Psychology Review*, *34*(1), 1–38. https://doi.org/10.1007/s10648-021-09626-5

Tight, M. (2021). Twenty-first century skills: meaning, usage and value. *European Journal of Higher Education*, *11*(2), 160–174. https://doi.org/10.1080/21568235.2020.1835517

Wang, X.-M., Yu, X.-H., Hwang, G.-J., & Hu, Q.-N. (2023). An online progressive peer assessment approach to project-based learning: A constructivist perspective. *Educational technology research and development*, *71*(5), 2073–2101. https://doi.org/10.1007/s11423-023-10257-6

Wang, Y., Xu, Z.-L., Lou, J.-Y., & Chen, K.-D. (2023). Factors influencing the complex problem-solving skills in reflective learning: results from partial least square structural equation modeling and fuzzy set qualitative comparative analysis. *BMC Medical Education*, *23*(1), 382. https://doi.org/10.1186/s12909-023-04326-w

Wardani, I. S., & Fiorintina, E. (2023). Building critical thinking skills of 21st century students through problem-based learning model. *JPI (Jurnal Pendidikan Indonesia)*, *12*(3), 461–470. https://doi.org/10.23887/jpiundiksha.v12i3.58789

https://doi.org/10.24191/smrj.v22i2 September.9861

Xing, W., Zhu, G., Arslan, O., Shim, J., & Popov, V. (2023). Using learning analytics to explore the multifaceted engagement in collaborative learning. *Journal of Computing in Higher Education*, *35*, 633–662. https://doi.org/10.1007/s12528-022-09343-0

Yang, D., Snelson, C., & Feng, S. (2023). Identifying computational thinking in students through project-based problem-solving activities. *Information Discovery and Delivery*, *51*(3), 293–305. https://doi.org/10.1108/IDD-09-2022-0091

Yue, J., Shang, Y., Cui, H., Liang, C., Wu, Q., Zhao, J., Wang, H., Han, D., & Zhu, Z. (2025). Visualization analysis of CBL application in Chinese and international medical education based on big data mining. *BMC Medical Education*, *25*(1), 402. https://doi.org/10.1186/s12909-025-06933-1

Zheng, L., Niu, J., Zhong, L., & Gyasi, J. F. (2023). The effectiveness of artificial intelligence on learning achievement and learning perception: A meta-analysis. *Interactive Learning Environments*, *31*(9), 5650–5664. https://doi.org/10.1080/10494820.2021.2015693