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Canonical Correlation Analysis for Understanding Foundational-Advanced Chemistry Classes Relationship and Their Role in Preparing Preservice Teacher

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Abstract

Mental models and the strength of basic chemistry concepts are the primary foundation for students to avoid obstacles in highly complex material. On the other hand, students' understanding of basic chemistry concepts has not been optimally developed, even though this situation impacts understanding complex material at the advanced level. However, simultaneous analysis of the relationship between foundational and advanced level courses using a statistical test approach is rarely done, even though this condition impacts learning success at the upper level. The purpose was to determine (1) the simultaneous relationship between prerequisite and advanced level courses, and (2) the contribution of each prerequisite course in predicting student academic achievement in advanced level classes. This study used a quantitative correlational design with canonical correlation analysis, involving introductory chemistry and school chemistry courses as prerequisites and basic organic chemistry and physical organic chemistry as advanced-level variables. Data collection used documentation techniques for students' cognitive learning outcomes in the chemistry education study program. The study results showed that the first canonical function (function 1) obtained a correlation of 0.99398 with $p = 0.000$ and an eigenvalue of 82.31551. This indicates a significant simultaneous relationship, with introductory chemistry contributing the most, while school chemistry contributed little. This study emphasises the importance of strengthening mastery of basic chemistry concepts and integrating pedagogical content to support student academic success and preparedness. This study provides a fundamental foundation for the importance of developing chemistry education programs that impact student academic performance while preparing them to face increasingly inclusive and connected global challenges through modern learning.

Keywords: advanced problem-solving skills, advanced competencies, canonical correlation analysis, cognitive learning outcomes, continuous learning program, design learning innovations, design learning strategies, sustainable learning.

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1. Introduction

One of the challenges in chemistry education is integrating students' macroscopic understanding with submicroscopic representations to develop concrete conceptual frameworks (Barke et al., 2012; Bucat & Mocerino, 2009). Although the macro level is relatively easy to grasp, Barke et al. (2009, 2012) assert that understanding at the submicroscopic level is significantly more cognitively impactful, particularly in building accurate mental models and supporting advanced problem-solving skills (Keiner & Graulich, 2021; Locatelli & Davidowitz, 2021; Parobek et al., 2021; Taber, 2013; Underwood et al., 2021;

Almubarak et al., 2025). Difficulty in mastering basic chemistry concepts often results in cognitive burden when students enter advanced courses, and performance memory does not support them in understanding complex matters at higher levels (Anmarkrud et al., 2019; Demirdöğen et al., 2023; Mayer & Moreno, 2003; van Nooijen et al., 2024; Almubarak et al., 2023).

Introductory chemistry is a course that plays a significant role in helping students' scientific reasoning abilities, especially fundamental concepts in chemistry, which are essential for prospective teachers in teaching complex topics. Furthermore, reasoning skills also support the development of 21st-century skills, such as problem-solving, creativity, critical thinking, and technological skills, while also training the process of constructing scientific mental models, so that obstacles in chemical material with high complexity can be faced, including particulate-level abilities (Barke et al., 2012; Gkitzia et al., 2020; Ortiz-nieves & Medina, 2014; Schwedler & Kaldewey, 2020; Taber, 2013; Xiaoge et al., 2019; Maghfiroh et al., 2024). Furthermore, pedagogical courses can train students to analyse content and design learning strategies responsive to student needs (Barke et al., 2012). The synergy between content and pedagogy is key to sustainable learning, significantly supporting students' skill development in advanced 21st-century topics (Fatihatussa'adah et al., 2024). However, the integrative influence of foundational and pedagogical courses on prospective teachers' advanced competencies has rarely been studied in depth, particularly using a comprehensive multivariate statistical approach (Ijirana et al., 2021).

This synergy is reflected in Wolfgang Klafk's (2006) didactic framework, which emphasises knowledge-oriented learning and a process of constructing structured meaning relevant to the present and the future. Klafki's theory asserts that didactic analysis consists of three fundamental questions in the planning and development of learning (Barke et al., 2012). First, content analysis (what) is the core content that students should learn. In this context, introductory chemistry and school chemistry strongly support students' conceptual strengthening in advanced courses. Second, didactic analysis (why and how), or why and how the material is delivered. This emphasises that instructors must consider the learning strategies used, considering their impact not only on pedagogical skills but also on strengthening understanding of the content itself. Third, instructional methodology (how to teach), or the approach used, can facilitate optimal student understanding. Klafki's theory emphasises that understanding the relationship between foundational, pedagogical, and advanced chemistry courses is a strategic step in developing sustainable and transformative learning. Therefore, the program implementation strategy must follow the results of content analysis and continuous learning needs, as part of renewal and adaptation to 21st-century learning (Kain et al., 2024; Mezirow, 1997; Vlachopoulos & Makri, 2024).

In chemistry learning, the focus is generally only on how to review learning outcomes as an essential part of the review, even though learning outcomes do not fully reflect the condition of the participants, because each participant has a different cognitive level. Differences in cognitive levels are a concern in chemistry learning, such as in the context of problem-solving. The difference between students who are expert problem solvers (experts) and those who are not (novices) lies in the breadth of their knowledge and ability to analyse problems (Chi et al., 1981; Larkin & Reif, 1979; J.-M. G. Rodriguez et al., 2019). This situation highlights differences in students' cognitive levels, where extensive knowledge provides greater access for students to interpret and find solutions (Chi et al., 1981). Systematic studies exploring the simultaneous contribution of introductory and pedagogical chemistry courses to readiness for advanced learning are still limited, especially using canonical analysis. The absence of this holistic analysis limits understanding of how early lecture experiences shape teaching effectiveness and the future cognitive development of prospective teachers.

Canonical correlation analysis is a multivariate approach increasingly used in engineering and industry to explore simultaneous linear relationships between two sets of variables. A study by Zheng et al. (2025) showed that canonical correlation supports learning effective discriminative representations between pairs of genuine and forged signatures, resulting in comparable or better performance than advanced verification systems. Another study showed that robust canonical correlation analysis has more stable performance on contaminated datasets than the classical canonical test (Alrawashdeh et al., 2024). In functional data analysis, the combination of SPEV-CC, which combines canonical correlation-based variable selection with function-to-function regression, has significantly reduced the mean square error and increased its practical usability in industrial applications (Yang et al., 2025). Another study also applied it to fault diagnosis in complex mechanical systems, showing excellent fault detection and isolation capabilities (Liang et al., 2025). A survey by Kudraszow et al. (2025) also developed a functional version of generalised canonical correlation analysis based on scatterplot matrices, which produces robust estimators.

Studies in educational contexts have shown that CCA can identify multidimensional relationship patterns that cannot be captured by simple correlation analysis (Holland & Piper, 2016). This method has also examined the relationship between personality, personal beliefs, and teaching practices in female teacher education students (Elmore & Ellett, 1978). Furthermore, canonical correlation was used to explore the relationship between high levels of imagination and the desire to try innovation, which are essential for a teacher (Elmore & Ellett, 1978). The same method was also used to examine the relationship between students' perceptions of various types of educator power and multiple modes of student complaint behaviour in university education (Mukherjee et al., 2009). However, these studies have limitations, so the results cannot be broadly generalised.

Several studies recommend that instructors study student needs to easily decide on relevant approaches or strategies in teaching, such as analyzing cognitive differences, designing assessment instruments, and other learning components (Asmussen et al., 2023; Braun & Graulich, 2024; Park et al., 2021; J. M. G. Rodriguez et al., 2020; Wackerly, 2021). Fulfilling student needs can be achieved by designing and developing various learning strategies so that students are equipped with scientific understanding, attitudes, technological skills, critical thinking, creativity, problem solving, and other skills, especially in the era of 21st-century learning (Kain et al., 2024; Ødegård et al., 2025; Park et al., 2021; Rahiman & Kodikal, 2024; Trilling-ling & Fadel, 2009; Vlachopoulos & Makri, 2024). Thus, understanding the relationship between basic and advanced level courses can help develop continuous learning programs and improve students' thinking in higher education.

Many studies have discussed the vital role of introductory chemistry courses in developing students' conceptual understanding and their contribution to pedagogical classes, particularly in improving teaching skills. However, studies analysing the relationship between the two and student readiness at advanced levels are minimal. Furthermore, while canonical correlation analysis has been widely applied in various fields to explore relationships between variables, its application in chemistry education to map the multidimensional contributions of basic and advanced chemistry courses, including pedagogical classes, has been largely unexplored (Setyaningsih et al., 2022). This indicates an urgent need for a more comprehensive approach to support the development of learning strategies relevant to student needs, a sustainable curriculum, and 21st-century skills. Furthermore, this study has the potential to serve as a foundation for developing modern learning and to support the exploration of learning appropriate to the local context while supporting the readiness of prospective teachers to face challenges in the workplace, both nationally and internationally.

Based on the explanation above, the research question is (a) What is the simultaneous relationship between prerequisite courses (Basic Chemistry and School Chemistry) and achievement in advanced courses (Basic Organic Chemistry and Physical Organic Chemistry); (b) To what extent does each prerequisite course contribute to predicting students' academic achievement in advanced classes.

2. Method

This study used a quantitative correlational design to explore the relationship between prerequisite courses (school chemistry and introductory chemistry) and advanced courses (organic chemistry and physical organic chemistry) among students majoring in chemistry education (Creswell, 2012; Hair et al., 2019). A canonical correlation design was chosen to identify the simultaneous contribution of prerequisite courses (foundational) to academic achievement in advanced classes. The study results can be used to develop needs-based learning while strengthening students' thinking skills.

The study sample consisted of chemistry education students at Lambung Mangkurat University, South Kalimantan, who had completed the prerequisite and advanced courses. The sampling technique used was purposive sampling, with the criteria being that students had passed both courses and had completed grades. Assessment data consisted of final student assessments from the official study program archives. Assessment components included project scores, midterm exams, and final exams, which were averaged to represent overall academic achievement.

The independent variables (X) consisted of grades in chemistry class 1 (X1) and introductory chemistry (X2), while Y was the dependent variable, namely grades in introductory organic chemistry (Y1) and physical organic chemistry (Y2). Data analysis used canonical correlation analysis to evaluate the simultaneous linear relationship between the two sets of variables (X and Y). This analysis included several calculations, such as canonical coefficients, canonical correlation loadings, and significance tests (Wilks' Lambda, Pillai's Trace, Hotelling's Trace, and Roy's

Largest Root). The analysis was conducted using SPSS version 25 statistical software with a significance level of $p < 0.05$ as the interpretation limit.

Ethically, student data was processed anonymously and used solely for study purposes, with permission from the study program. Student identities were fully protected to avoid risking data confidentiality, following ethical research principles applicable in higher education.

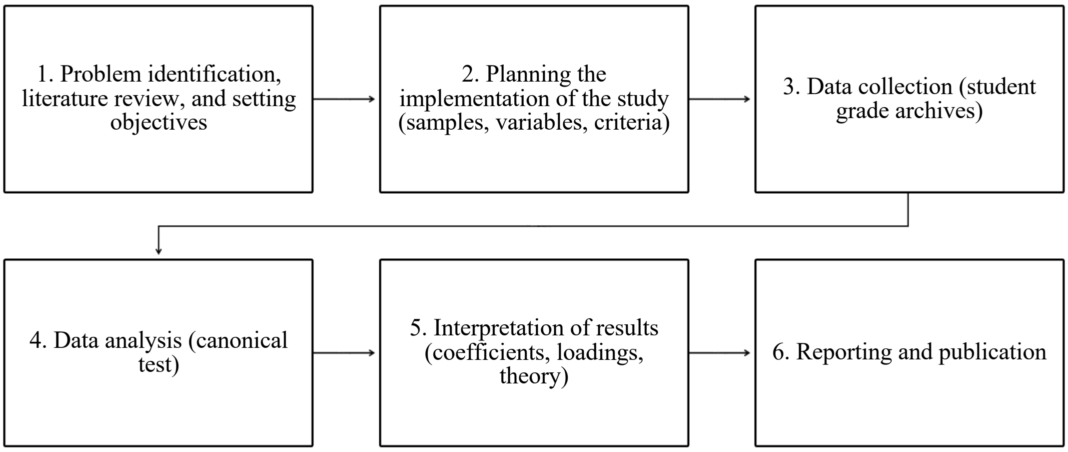

Figure 1. The procedure for conducting the study is illustrated visually in the research stages.

3. Result and Discussion

a. What is the simultaneous relationship between prerequisite courses (Basic Chemistry and School Chemistry) and the achievement of advanced courses (Basic Organic Chemistry and Physical Organic Chemistry)?

The results in Table 1 show that two canonical functions were evaluated. The first canonical function (function 1) obtained a value of 0.99398 with p = 0.000, indicating a highly significant relationship. Function 1 for "Eigenvalue" obtained a value of 82.31551, indicating that this function explains 99.95% of the cumulative variation in the data. Canonical correlation function 2 obtained a value of 0.19708 with p = 0.345, indicating statistical insignificance. Therefore, the first function can be used for further interpretation, while the second function is irrelevant in the context of this analysis. The Wilks' Lambda results support this condition, with the canonical function producing an F value of 91.41359 with a significance of p = 0.000. Therefore, the first canonical function can explain the two sets of variables, while the second function cannot.

Table 1. Calculation for the determination of Canonical Functions

Eigenvalues and Canonical Correlations					
Root No.	Eigenvalue	Pct.	Cum. Pct.	Canon Cor.	Sq. Cor
1	82.31551	99.95093	99.95093	.99398	.98800
2	.04041	.04907	100.00000	.19708	.03884
Dimension Reduction Analysis					
Roots	**Wilks L.**	**F**	**Hypoth. DF**	**Error DF**	**Sig. of F**
1 To 2	.01154	91.41359	4.00	44.00	0.000
2 To 2	.96116	.92940	1.00	23.00	0.345

Table 2 shows that the results of the Pillai's Trace, Hotellings's Trace, Wilks' Lambda, and Roy's Largest Root statistical tests are statistically significant with a p-value of <0.05. This analysis indicates a relationship between the independent and dependent variables in the canonical model structure. For example, an indication that the variance explained by the canonical function is significant is obtained from the F value = 12.13427 and p = 0.000 by Pillai's Trace value (1.02684). Then, Wilks' Lambda gives a value of 0.01154 with an approximate F = 91.41359 and p = 0.000, which indicates that most variables can be explained significantly, and this is one of the leading indicators in canonical analysis. For Hotelling's Trace, the value of 82.35592, F = 432.36860, and p = 0.000 is obtained, and the relationship between variables is firm in the canonical model. Finally, to get a value of 0.9880, Roy's largest root with F = significant at p = 0.000, the most considerable canonical function is substantial and contributory. Thus, this finding supports that both canonical functions can be considered in the further analysis because they have a significant relationship simultaneously.

Table 2. Multivariate Tests of Significance

Test Name	Value	Exact F	Hypoth. DF	Error DF	Sig. of F
Pillais	.02129	.23929	2.00	22.00	.789
Hotellings	.02175	.23929	2.00	22.00	.789
Wilks	.97871	.23929	2.00	22.00	.789
Roys	.02129				

b. To what extent does each prerequisite course contribute to predicting students' academic achievement in advanced courses?

Table 3 shows that the contribution of each variable is different in the canonical model. Based on the results of the "standardized canonical coefficients for DEPENDENT variables" in the second function, the physical organic chemistry variable (Y2) has a high correlation value of 0.87444, meaning that Y2 is dominantly contributory to the second canonical function. On the other hand, the more minor contribution to the second function is the variable Y1, with a coefficient value of 0.14341. This finding confirms that the second canonical function represents the relationship involving the variable Y2 more than Y1. On the other hand, for the independent variable, X2 (general chemistry) has a value of 0.85133 based on the standardized canonical coefficient. This value indicates that the function contributes very strongly. In contrast, X1 has a lower coefficient value of -1.31622, meaning that the contribution given is very small or negative with the first function. A higher contribution is provided by X2 with a coefficient value of 1.00385 on the second function compared to -0.00594 from X1.

Thus, table 3 shows that variable X2 (general chemistry) significantly influences the first canonical function. In contrast, variable Y2 (physical organic chemistry) significantly impacts the second function more. The indication is that each variable has a specific relationship to each canonical function. Therefore, this finding can be the focus of subsequent interpretations to explain the relationship between sets of independent and dependent variables.

Table 3. Raw Canonical Coefficients

Standardized Canonical Coefficients for DEPENDENT Variables		
Variable	**1**	**2**
Y1	-1.93142	.14341
Y2	2.72809	.87444
Raw canonical coefficients for COVARIATES function no.		
Covariates	**1**	**2**
X1	-.28046	-.00127
X2	.27439	.32355
Standardized Canonical Coefficients for COVARIATES CAN. VAR.		
Covariates	**1**	**2**
X1	-1.31622	-.00594
X2	.85133	1.00385

Table 4 results from the canonical loading calculation related to strengthening the relationship between variable data. The results show that the independent and dependent variables strongly correlate with a higher canonical value on variable X2 (general chemistry) of 0.9999 in the table "Correlation between Covariates and Canonical Variables". This finding confirms that X2 contributes most to the second canonical function, while variable X1 = 0.64679 has a lower contribution. In terms of dependent variables in the table, both variables have a high correlation to the second canonical function, such as Y2 (physical organic chemistry), which is highly correlated with a value of 0.99725 and followed by a value of 0.89227 from organic chemistry (Y1). Both dependent variables have a close relationship in the second canonical function, with the most dominant contribution being Y2. Thus, student success in basic chemistry courses can be a predictor of their success during advanced material lectures.

Table 4. Canonical Loading

Correlation between COVARIATES and Canonical Variables CAN. VAR.		
Covariate	**1**	**2**
X1	-.76267	.64679
X2	-.00451	.99999
Correlation between DEPENDENT and Canonical Variables Function No.		
Variables	**1**	**2**
Y1	-.45150	.89227
X2	.07405	.99725

Prerequisite courses and advanced courses have a significant relationship based on statistical analysis. The first canonical correlation was 0.99398 for function 1, with a significance level of <0.05 (p=0.000, individually substantial). This correlation confirms that introductory chemistry courses (X2) support sustainable learning, particularly in physical organic chemistry (Y2). This value indicates that basic chemistry material substantially prepares students for advanced material. The conceptual nature of introductory chemistry provides a solid foundation for students to delve deeper into other, more advanced chemistry materials. This contribution is evident in the canonical coefficient of 0.85133 (Standardised canonical coefficients for COVARIATES CAN. VAR.). This aligns with mastering fundamental chemistry concepts as a foundation for higher-order thinking in higher education. In chemistry education, learning based on the representational level is the primary foundation for building scientific mental models (Barke et al., 2012).

By possessing basic knowledge and representational competence, students have an easier time understanding and interpreting phenomena from the macro to the symbolic level (Cheng & Gilbert, 2009; Keiner & Graulich, 2021; Taber, 2001), whereas previous studies tended to focus on submicroscopic applications. Specifically, introductory chemistry demonstrates a dominant contribution compared to school chemistry. This is because introductory chemistry studies many fundamental concepts, such as atomic structure, chemical bonding, fundamental chemical laws, stoichiometry, reaction mechanisms, and reaction rates, which serve as the primary basis for studying organic chemistry as a process of building mental models. Taber (2012) emphasised that effective mental structures and models are constructed from mastery of fundamental chemical concepts. Improving mental models also plays an essential role in helping students gain a deep understanding of chemistry and its application in society (Barke et al., 2009, 2012; Mezirow, 1997). This dominance indicates that mastery of pure chemistry content learned and obtained from introductory courses influences students' success in understanding advanced material.

In contrast, school chemistry 1 (X1) contributed less, which needs to be considered and addressed in the teaching context. One possible reason is that this course emphasises pedagogical approaches, lesson planning, and delivery methods rather than reinforcing in-depth chemistry concepts. School chemistry is designed to provide students with pedagogical insight and competency as future teachers. The experience of studying school chemistry 1 offers theoretical and practical literacy to prepare students to master chemistry concepts, analyse learning difficulties in specific chemistry topics, and understand chemistry learning design based on the needs of secondary-level students. This demonstrates the potential for strengthening the structure of school chemistry learning so that it focuses not only on teaching strategies but also on deepening conceptual understanding contextually. Integration of content and pedagogy is crucial to support continuous learning and build solid mental models, in line with Klafki's didactic framework, which emphasises the importance of the interconnectedness of "what," "why," and "how" in lesson planning.

Following Wolfgang Klafki's (1980) didactic framework, for content analysis (what), the results show that introductory chemistry (X2) significantly contributes to basic organic chemistry (Y1) and physical organic chemistry (Y2) courses. This finding confirms that introductory chemistry has a substantial weight in supporting students' understanding of advanced concepts with high complexity. Therefore, introductory chemistry is key for students in building scientific mental models and supporting continuous learning. For didactic analysis (why and how), this context highlights the school chemistry course (X1). The canonical test shows that X1 contributes less than X2, thus concluding that the focus of X1 should be building integration between students' conceptual understanding and pedagogical skills. In Klafki's thinking, this finding emphasises the importance of considering learning strategies to accommodate students' conceptual understanding and teaching skills. Although statistically, school chemistry contributes less than introductory chemistry, its presence has a very crucial role in building students' mental models, considering that learning science, such as chemistry, requires various approaches to understand chemical materials, especially at the submicroscopic level (Keiner & Graulich, 2021; Schwedler & Kaldewey, 2020; Widing et al., 2023).

This study confirms that students with a strong foundation in chemistry are better prepared for advanced material and can handle cognitive load and analytical thinking. This finding is relevant to the literature, which states that students' difficulties in understanding advanced concepts are often rooted in a weak understanding of introductory chemistry and submicroscopic representations. For example, to practice problem-solving skills, these skills tend to be trained using representational concepts through graphs, writing, reaction stages, arrow notation, and other methods (Bruce et al., 2022; Hunter et al., 2021; Shabrina et al., 2023; Watts et al., 2020). However, these concepts have not fully trained students' elaboration skills in understanding concepts at the specific level (Dood & Watts, 2022). Some instructors have not intended to practice representational concepts because they believe it could disrupt the duration of class material completion (Popova & Jones, 2021). Therefore, training or understanding the level of representation is not enough without knowing the students' needs, but a more relevant approach is needed to address the problem.

Regarding methodological contribution (how to teach), the use of canonical correlation adds value to this study. This method allows for the analysis of simultaneous relationships between sets of variables, which cannot be accommodated by simple correlation analysis or linear regression. Its application in the context of chemistry education, particularly the exploration of the relationship between prerequisite courses and advanced achievement, makes this study crucial for providing instructors with additional insights into chemistry learning development strategies relevant to 21st-century learning (Prastikawati et al., 2024). This study also confirms that optimal academic performance at a high level can be enhanced by meeting performance in foundational-level courses. In cognitive load theory, students with optimal mastery and understanding of introductory chemistry are more likely to reduce cognitive load when facing more complex problems. A strong foundation of understanding can allocate students' cognitive resources to analyse advanced concepts (Anmarkrud et al., 2019; Mayer & Moreno, 2003; Paas et al., 2016; van Nooijen et al., 2024).

This study has practical implications for the design of chemistry learning, even at the curriculum level, where previous studies have shown that canonical chemistry is widely used in various engineering and industrial fields (Alrawashdeh et al., 2024; Kudraszow et al., 2025; Yang et al., 2025; Zheng et al., 2025). In education, the context of its use is not in the analysis of simultaneous relationships between materials, but rather in perceptions, personalities, teaching practices, behaviours, etc. (Elmore & Ellett, 1978; Holland &

Piper, 2016; Mukherjee et al., 2009). Therefore, it is necessary to strengthen the conceptual content in introductory chemistry and innovation in school chemistry learning so that it not only trains pedagogical aspects but also supports the in-depth understanding needed in advanced chemistry courses. These findings also support the development of 21st-century skills, such as critical thinking, creativity, problem-solving, collaboration, and digital literacy, which are essential for prospective chemistry teachers to face various global challenges (Kain et al., 2024; Hidayat et al., 2025; Ødegård et al., 2025; Vlachopoulos & Makri, 2024).

Thus, this study provides a theoretical contribution by explaining the relationship between prerequisite and advanced courses, as well as a practical contribution by supporting learning renewal, curriculum strengthening, and continuous learning, as well as strengthening students' readiness as future adaptive and transformative professional educators.

c. Limitations, Significance, New Perceptions

Although the results of this study are considered significant, particularly the analysis of the relationship between basic and advanced chemistry courses, several limitations still require consideration. First, this study used a correlational approach, so causal conclusions cannot be drawn directly between the independent and dependent variables. Second, the sample size does not fully represent the entire population of chemistry education students. Therefore, further investigation with a larger sample size is highly recommended in future studies. Third, aspects of the lecturer's teaching style or learning strategies were not included as pedagogical variables, as these factors significantly influence student academic performance. Longitudinal or experimental designs are highly recommended for further study to explore causal relationships and consider broader contextual factors in chemistry learning.

The results of this study need to be interpreted very carefully, considering the study's design, which is limited to one study program and the use of a solely quantitative approach. Furthermore, although all quotes and paraphrases in this article have been compiled with efforts to maintain the accuracy of the source's meaning, readers are still advised to read the primary sources directly to gain a more comprehensive understanding and avoid potential distortion of interpretation. These findings are expected to be a starting point for further studies with a broader sample scope and a more varied approach.

The canonical correlation test has demonstrated a significant relationship between basic and advanced chemistry courses. It allows instructors and curriculum developers to design learning innovations in higher education settings. For example, integrating problem-solving-based learning, needs-based learning, and applying multiple representations can facilitate the construction of student structures and mental models, thereby achieving a deeper understanding of chemistry material. This integration can potentially train students to solve problems, especially when experiencing more complex learning in advanced courses.

Overall, the practical implications of the study results are improved quality of content-based programs and curricula, which are also aligned with student needs. This approach can strengthen student competencies in the local context while contributing to global challenges. Continuous chemistry learning can be adopted in various universities, considering that analytical and synthetic skills are key elements for students to adapt to the diverse challenges of the international workplace. Therefore, integrating collaboration, problem-solving, inclusiveness, and adaptive skills into learning is a strategic step in preparing students for 21st-century learning. Integration goes beyond simply understanding chemistry content conceptually; it also fosters the ability to implement it practically and innovatively in the real world.

4. Conclusion

The study results indicate a simultaneous relationship between prerequisite courses (introductory chemistry and school chemistry) and achievement in advanced classes (introductory organic chemistry and physical organic chemistry). Basic chemistry contributes dominantly as the primary conceptual foundation, while school chemistry has a lesser contribution due to its focus on pedagogical aspects. This finding reinforces the importance of students mastering basic chemistry concepts in building their readiness to face complex material at advanced levels. Although its effect is statistically minor, school chemistry is still essential for developing students' teaching skills aligned with the challenges of 21st-century education.

This study acknowledges the existence of limitations, including the data collected from only one university, which limits the generalizability of the findings. Furthermore, the quantitative approach does not qualitatively capture the dynamics of student perceptions. Future studies should involve various study programs, expand the geographic area, and incorporate qualitative methods to deepen understanding of non-academic factors that influence student achievement.

Practically, this study can serve as a basis for developing learning strategies and curriculum design that balance conceptual and pedagogical content. Strengthening school chemistry content is necessary, such as integrating pure laboratory work, contextual approaches, or various problem-solving-based approaches. The results of this study can also be used as a basis for developing a continuous evaluation program for prospective chemistry teachers to prepare them better to face the challenges of 21st-century education, both nationally and internationally. Developing and training students' competencies from the time they begin their education provides the space for forming a superior, technologically savvy, creative, critical, and diversity-aware generation in the future, while simultaneously achieving sustainable learning.

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