International Journal of Science and Mathematics Education
https://doi.org/10.1007/s10763-024-10523-w

The Effect of Interventions Teaching Chemical Kinetics on Students' Academic Performance: A Meta-Analysis Study

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Received: 11 March 2024 / Accepted: 30 October 2024

Abstract
Science educators have looked for alternative pedagogies to facilitate student learning of chemical kinetics and tested their effects on academic performance. However, science education literature has not evaluated these interventions teaching chemical kinetics through a meta-analysis. Therefore, this study aimed to meta-analytically investigate the effect of the interventions on students' academic performance. Through common academic databases and manual search, the authors identified 26 intervention (experimental) studies and inserted their statistical data into Comprehensive Meta-Analysis (CMA) statistics software to produce Hedges' g values. The findings of the current meta-analysis indicated that the overall effect-size of the interventions was 1.042, which points to a large effect. Also, the findings of moderator variables (educational level, implementation duration and type of intervention) revealed non-significant differences at the students' academic performance as a result of the interventions. The classifications of the effect-sizes of the moderator variables showed that such interventions as inquiry-based learning are more fruitful than computer-assisted instruction and cooperative learning even though all of the intervention types are more effective in developing students' academic performance than the traditional or existing instruction. Given a broad range of the effect sizes (from 0.125 to 2.475), it can be concluded that controlled (e.g., implementation duration, preferred intervention type and educational level) and uncontrolled variables (e.g., preparedness level, pre-requests of learning, and cultural context) influence the effectiveness of the interventions. Given the evidence-based results of the current meta-analysis, future studies should re-consider key issues (e.g., controlled and uncontrolled variables) underpinning the nature of an effective intervention to better accomplish the related goals or learning outcomes of chemical kinetics.

Keywords Academic performance · Chemistry education · Chemical kinetics · Intervention · Meta-analysis

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Published online: 02 December 2024

Introduction

The topic 'chemical kinetics' acts as a milestone to grasp advanced chemistry concepts or topics (e.g., chemical change, equilibrium, and thermodynamics) (Bain & Towns, 2016). Further, it helps students understand interdisciplinary topics or concepts such as enzymes, biochemical reactions in human body and/or animals, and food production and ripen of fruit and vegetables (Ebbing, 1993; Sinan, 2007; Steele, 2004). Since it has a great potential to represent macroscopic, sub-microscopic, and symbolic levels of any chemical reaction or process, it gives an opportunity for students to contextually link their observations with theoretical aspects (e.g., sub-microscopic and symbolic) of chemistry (Cakmakci et al., 2006; Habiddin & Page, 2021; Hamnell-Pamment, 2024; Johnstone, 1991; Taber, 2013; Talanquer, 2011). For example, after observing fast and slow chemical reactions, students are able to symbolically write down their chemical equations, explain them via particulate nature of matter and collision theory and mathematically model them through graphs or formulas. Hence, it brings together various observations (e.g., time and models related to composition, structure, and energy) and visualizations through mathematical, conceptual, or contextual approaches to achieve multi-dimensional framework of chemistry (Bain & Towns, 2016; Talanquer, 2011).

Difficulties and Challenges of Learning and Teaching Chemical Kinetics

Given the importance of chemical kinetics or rate of reaction, chemistry curricula generally introduce its fundamental concepts at high school level while reserving advanced concepts or issues for undergraduate one (Bain & Towns, 2016; Milli Egitim Bakanligi, 2018). However, previous studies have reported that high school and undergraduate students have difficulties comprehending the topic 'chemical kinetics' or related concepts (Bain & Towns, 2016). For instance, students were found to hold several alternative conceptions on definition of the rate of reaction (Cakmakci, 2005; Çalik et al., 2010), the effect(s) of some variables (temperature, concentration, catalyst, and surface area) on the rate of reaction (Cakmakci, 2005; Hackling & Garnett, 1985; İcik, 2003; Kıngır & Geban, 2012; Kolomuç & Çalık, 2012; Nakiboğlu et al., 2002), the relationship between the rate of reaction and reaction time (Cakmakci, 2005; Taştan et al., 2010), reaction mechanism or reaction step determining the rate of reaction (Cakmakci, 2005; Taştan et al., 2010), the role(s) of activation energy and collision theory on the rate of reaction (Alkan & Benlikaya, 2004; Banerjee, 1991; Cakmakci & Leach, 2005; Hackling & Garnett, 1985; Nakiboğlu et al., 2002; Taştan et al., 2010). The existing studies have also referred to several factors resulting in alternative conceptions or preventing meaningful learning of chemical kinetics. The first factor is the role(s) of mathematics skills, mathematical understanding and proficiency in explaining relevant kinetics topics or concepts (Adesoji & Ibraheem, 2009; Ahiakwo & Isiguzo, 2015; Bain & Towns, 2016; Çam et al., 2015; Rodriguez et al., 2020). For example, Rodriguez et al. (2020), who explored how undergraduate students understand and use mathematics in chemical kinetics, found compartmentalization that prevents the meaningful blending of knowledge because chemistry and mathematics ideas are siloed. Similarly, Ahiakwo and Isiguzo (2015) and Çam et al. (2015) reported that their participants' mathematics skills (senior secondary and university chemistry students from Nigeria; pre-service science teachers from Türkiye, respectively) were poor to conduct basic computations (e.g., calculating mass of reactants over time and measuring the rate of reaction). Likewise, Adesoji and Ibraheem (2009) found that students with high mathematical ability outperformed those with medium and low abilities. Thus, they concluded that student's mathematical background plays a significant role at learning chemical kinetics.

The second factor is the abstract and complex nature of chemical kinetics (Justi, 2002). Because the topic 'chemical kinetics' involves such abstract concepts as collision of particles, activation energy, rate equation, rate constant and reaction mechanism, students need to conceptualize its abstract and complex nature. Thereby, this factor is a milestone to explain how a chemical reaction proceeds and changes. The third factor is students' inability to visualize any chemical reaction at sub-microscopic level or use the particulate nature of matter within the topic 'chemical kinetics' (Cakmakci et al., 2006; Langbeheim et al., 2023; Michalisková & Prokša, 2018). For example, Cakmakci et al. (2005), who examined the development of students' understanding of chemical kinetics from secondary to university level, addressed that majority of the students tended to use macroscopic properties in their explanations even though they were encouraged to consider the phenomenon in terms of particles (sub-microscopic level). This means that students should imagine any chemical reaction at sub-microscopic level and deploy the particulate nature of matter to conceptually and contextually grasp the topic 'chemical kinetics.' The fourth factor is a dilemma between daily life and scientific language or between chemical and other scientific terms (e.g., Michalisková & Prokša, 2018). For instance, Michalisková and Prokša (2018), who elicited Slovak students' understanding of the topic "rate of reaction", found that students have deficiencies at distinguishing chemical terms from daily-life language or other scientific terms. That is, they tended to associate the term "rate of chemical reaction" with bodies in motion, which they had known from physics lessons and everyday life. This means that students need to differentiate chemical terms from daily-life language and other scientific terms to correctly build their scientific vocabulary and communicate with peers and teachers (Kıryak et al., 2024). The fifth factor is incompetence of traditional (e.g., teacher-centered) or existing (suggested by science curriculum) instruction in improving students' understanding of the topic 'chemical kinetics' (Bain & Towns, 2016). This shows that teacher-centered or existing instruction has little contribution or limited effect on their conceptual and meaningful understanding of the topic. As a matter of fact, Bain and Towns (2016), who reviewed chemical kinetics studies, implied that every new teaching intervention is more effective in conceptually teaching the topic 'chemical kinetics' and remedying relevant alternative conceptions than a traditional classroom approach. Given the findings of Bain and Towns (2016), the topic calls for alternative and new pedagogies or approaches that differ from traditional or existing one.

Fortunately, some of the earlier studies have challenged the foregoing alternative conceptions and difficulties of chemical kinetics and employed diverse pedagogical approaches and instructional implementations with different samples (grade 9 to university) and implementation durations (one week to seven week). For example, they have tested cooperative learning (Adesoji & Ibraheem, 2009; Koç, 2009; Taştan Kırık & Boz, 2012), computer-assisted instruction (Fernando & Mahanama, 2021; Olakanmi, 2015), inquiry-based learning (Cakmakci & Aydogdu, 2011; Cetin, 2014; Yalçınkaya et al., 2012), self-regulated learning (Olakanmi, 2017), pocket book (Handayani et al., 2021), reflective pedagogy (Setyowati & Louise, 2018), context-based learning (Karpudewan & Mathanasegaran, 2018), analogical instruction (as conceptual change approach) (Tsegaye et al., 2020) and a combination of different learning techniques or models called an enriched learning environment (Balcı, 2006; Çalik et al., 2010; Kıngır & Geban, 2012; Murni et al., 2022). As expected, the interventions teaching the topic 'chemical kinetics' put forth a clear message that the aforementioned instructional approaches or methods or strategies are superior to a traditional classroom approach (Bain & Towns, 2016). However, the question "To what extent are they improving students' academic performance?" is still a missing point in the relevant literature. Such an unexplored issue calls for the current meta-analysis study to investigate the effect of the interventions on students' academic performance. Further, the diversity of the interventions has appeared 'type of intervention' moderator variable for the current meta-analysis. Likewise, they studied with different educational levels, e.g., grade 9 (e.g., Olakanmi, 2008), grade 10 (Kıngır & Geban, 2012), grade 11 (e.g., Çalik et al., 2010; Handayani et al., 2021), grade 13 (Fernando & Mahanama, 2021), first-year science student teachers (e.g., Cakmakci & Aydogdu, 2011; Çubukçu, 2023; Koç, 2009) or pre-service science teachers (e.g., Muchtar et al., 2020). The variety in the samples of the interventions has emerged "educational level" moderator variable. Similarly, their implementation durations were varied: one (Olakanmi, 2008), two (Cakmakci & Aydogdu, 2011), three (e.g., Çalik et al., 2010; Olakanmi, 2017), four (e.g., Kaya, 2011; Kıngır & Geban, 2012), five (Tsegaye et al., 2020), six (e.g., Adesoji & Ibraheem, 2009; Çubukçu, 2023; Taştan Kırık & Boz, 2012), and seven weeks (Yalçınkaya et al., 2012). This variation has emerged "implementation duration" moderator variable for the present study. Meanwhile, previous chemical kinetics studies have generally focused on students' understanding (e.g., Çalik et al., 2010; Fernando & Mahanama, 2021; Gongden et al., 2019; Handayani et al., 2021; Karpudevan & Mathanasegaran, 2018) or achievement (Adesoji & Ibraheem, 2009; Muchtar et al., 2020; Murni et al., 2022; Olakanmi, 2017; Olakanmi & Gumbo, 2017) as dependent variable and interchangeably used these terms to state academic performance. Therefore, the authors preferred the term "academic performance" that involves achievement and understanding as content knowledge of the topic 'chemical kinetics.'

Rationale and Significance of the Study

Since 'chemical kinetics' topic has the power to provide insight into the nature of chemical reactions and processes, it ties macroscopic properties (observable phenomena) with sub-microscopic and symbolic levels and mathematically models theoretical aspects of chemistry (Bain & Towns, 2016; Çakmakçi et al., 2006). Given its complexity, importance, and prominence within the field of chemistry, it is initially taught at high school and then university (Bain & Towns, 2016). For this reason, identifying students' understanding of chemical kinetics and improving them with alternative pedagogical approaches or methods are crucial to formulate, develop, and implement effective pedagogies for chemistry learning (Ahmad et al., 2023). Hence, chemistry education not only helps students overcome their own learning barriers but also makes chemistry career attractive for them (Ahmad et al., 2023; Ültay & Çalık, 2012). Of course, this needs a sustainable educational approach to effectively use time, effort and budget for teaching and learning chemistry. Systematic reviews and meta-analysis studies may provide invaluable results to illuminate the present chemistry education research and re-consider how to make it sustainable and more achievable. For example, chemistry educators may focus on extreme effect-sizes of the interventions, and handle significant and non-significant moderator variables for future research and offer any convenient teaching design for chemistry learning based on the nature of the topic, and the characteristics of the intervention types and moderator variables.

Given the significance of 'chemical kinetics' as a topic of chemistry learning, Bain and Towns (2016) comprehensively reviewed a total of 34 studies at secondary education and undergraduate levels. They pointed out that the studies concerning chemical kinetics have two main perspectives as student understanding and instructional approaches to teaching. Also, they noted that every instructional approach outperforms a traditional one. However, this message lacks a standard measurement value or criterion (e.g., Hedges' g). Therefore, this statement calls for a meta-analysis to statistically calculate the effectiveness of the interventions teaching chemical kinetics in developing academic performance and compare them with moderator variables such as educational level, implementation duration and type of intervention. Hence, the current study is expected to shed more light on practical significance of the interventions in a very organized and systematic way (Borenstein et al., 2009; Lipsey & Wilson, 2001). Likewise, computing overall and individual effect-sizes of the interventions and exploring the effects of moderator variables (e.g., educational level, implementation duration and type of intervention) on academic performance, the current meta-analysis provides invaluable results for chemistry educators, chemistry teachers and curriculum developers. For example, they can use the findings of the current meta-analysis to develop a roadmap for teaching the topic 'chemical kinetics' and selecting the most appropriate one in regard to their own contexts and contents or making a decision about their chemistry curricula. Also, future research may focus on extreme values (the lowest and highest ones) in the interventions to qualitatively deepen their findings and cultivate their reasons or inferences in their own studies. Similarly, given type of intervention, researchers and teachers may look for alternative pedagogical approaches to better teach the topic 'chemical kinetics' instead of repeating what is already known or the tested ones. To sum up, the present study may inform future decisions and discussions about the effectiveness of the interventions by providing evidence with standard measurement value (e.g., effect-size—Hedges' g).

The Purpose and Research Questions of the Study

The study aimed to meta-analytically investigate the effect of the interventions teaching chemical kinetics on students' academic performance. The following research questions guided the current study:

1. To what extent do the interventions affect students' academic performance?
2. Are there any significant differences between the mean effect-sizes of moderator variables (e.g., educational level, implementation duration and type of intervention) regarding the interventions?
3. What are descriptive differences between the mean effect sizes of the individual moderator levels in regard to the effect-size classification?

Methodology

This study recruited a meta-analysis to explore the effect of the interventions on students' academic performance. Thereby, it collected the findings of the interventions with quasi-experimental design and statistically analyzed them to examine their practical significance through effect-sizes (Hedges' g) (Borenstein et al., 2009; Çalik et al., 2023; Çalik & Wiyarsi, 2024; Ellis, 2010; Karadag, 2020; Üstün & Eryılmaz, 2014). Finally, through the meta-analysis, it systematically handled relevant studies to unveil any effect or relationship between dependent (e.g., academic performance) and independent (e.g., interventions teaching chemical kinetics) variables (Atasoy, 2021; Lipsey & Wilson, 2001; Sezen-Vekli & Çalik, 2023; Üstün & Eryılmaz, 2014).

Data Collection

The authors followed the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines to collect data (Page et al., 2021). They initially decided information sources (e.g., educational databases–ERIC, EBSCO, Springer Link, Taylor & Francis, Wiley Online Library Full Collection, Science Direct, ProQuest Dissertations and Theses Global, Sage Journals, Google Scholar, Scopus, and the Higher Education Council (HEC) Dissertations and Theses in Türkiye), search strategy (e.g., the use of keyword patterns for related databases through a period of 1990–2023), inclusion (e.g., the interventions, understanding and achievement as learning outcomes, and publication language—Turkish and English) and exclusion criteria (for example, different dependent variables– attitude, critical thinking skill or mental model; pre-experimental design). That is, the authors employed some keywords ('chemical kinetics or rate of reaction,' and 'experimental or intervention or treatment' and 'chemistry education or science education') via the keyword patterns from the abstracts (see Supplementary Material for the list of all keyword patterns) to retrieve related studies from the selected educational databases. Also, they conducted a manual search of recently published studies and dissertations by checking their references. Thus, they tried to find missing studies and extend the scope and efficiency of the meta-analysis study. The first round of the search process took about 4 months and completed on March 1, 2023. Then, the authors conducted another round to update the corpus of the data by screening newly published studies on January 15, 2024. Furthermore, they paid more attention to duplicated papers, which were indexed in more than one database or produced from dissertations. Therefore, the authors excluded three duplicated studies from the corpus of the data. Then, they carefully applied the inclusion criteria to the corpus of the data. Hence, they excluded 27 studies with different dependent variables (i.e., attitude, critical thinking skill or mental model) (Amelia et al., 2020; Chairam et al., 2015; Lathifa, 2020; Lathifa et al., 2021; Nurfidayanti & Yonata, 2022) and pre-experimental design (Kuzey, 2013; Lati et al., 2012; Sari et al., 2020; Supasorn et al., 2022; Supasorn & Promarak, 2015; Yasukham et al., 2011). Next, they checked the studies to decide whether they include sufficient data to produce their effect-sizes. Thus, they dropped out another 22 studies (for example, Habiddin et al., 2023), which did not have enough data (e.g., mean, standard deviation, sample size, p-value or t-value) to calculate Hedges' g value or only reported their findings with descriptive statistics (e.g., frequency and percentage) or non-parametric analysis (Mann–Whitney U test). During the selection process, the authors independently assessed the corpus of the data and weekly negotiated with each other to come up with absolute agreement. Such a strict peer scrutiny of the data appeared 26 intervention (experimental) studies published from 2006 to 2023 that focused on high school and university levels and examined the effect of the interventions on academic performance. Further, all of them used the same questions in pre- and post-test through the experimental design. Figure 1 summarizes the selection process.

Four of the studies had several experimental groups (Kaya, 2011; Koç, 2009; Murni et al., 2022; Taştan Kırık & Boz, 2012) where the same intervention was conducted with different cohorts or schools (Anatolian and regular high schools for Taştan Kırık and Boz (2012) and high and low achieving schools for Murni et al. (2022) or its different versions (e.g., Jigsaw puzzle and group investigation for cooperative learning for Koç, 2009) or different data collection tools (e.g., rate of reaction concept test and rate of reaction achievement test for Kaya, 2011) were used. In this situation, the authors calculated combined effect-sizes for the same intervention types by using the study as the unit of analysis under the 'subgroups within the study' option. Phrased differently, since the aforementioned studies pursued the same intervention type for their experimental groups (e.g., the enriched learning environment and cooperative learning), the authors generated only one combined effect-size for the type of intervention. Hence, they intended to deal with inflating impacts of individual studies on the overall effect-size. The characteristics of the studies under investigation are displayed in Table 1.

Data Analysis

The authors exploited a coding form (e.g., reference of the paper, sample size, grade, dependent and independent variables and quantitative values—mean, standard deviation, t and p) to clearly extract the relevant data and facilitate coding procedure

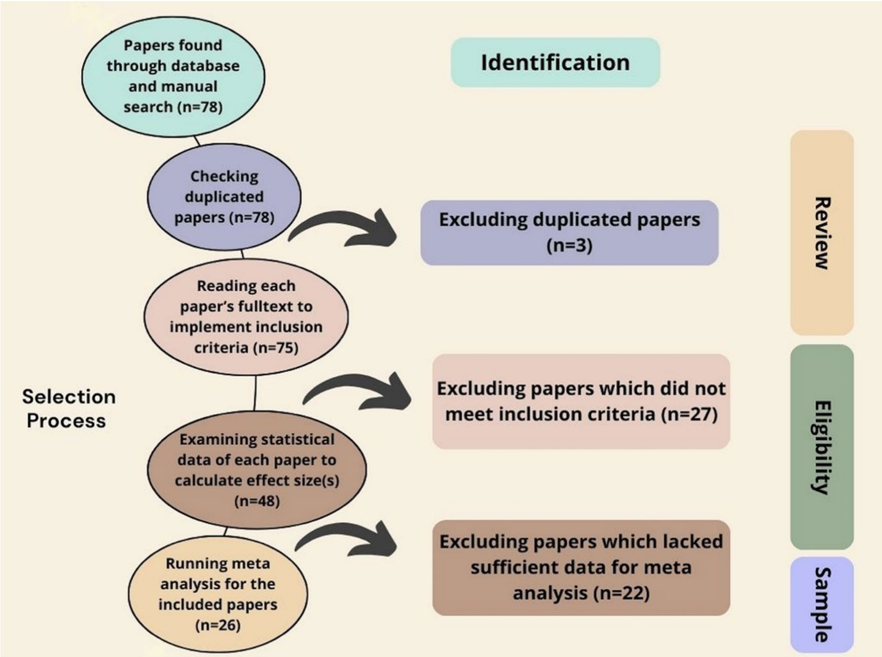

Fig. 1 Flow chart of the selection process

(Karadag, 2020). Also, they probed educational level and type of intervention (see Table S1 in Supplementary Material) using the definitions reported by Çalik et al. (2023, 2024). At the next stage, they conformed the studies' implementation durations to a standard criterion (e.g., a week covers 2 class-hours) to test the related moderator. In this way, they independently coded the studies to calculate the inter-rater consistency value. The agreement rate was found to be 92%, which reveals a high consistency. Any disagreement was resolved through negotiation.

Because Hedges' g is more accurate and less biased for a small sample size than Cohen's d (Borenstein et al., 2009; Güler et al., 2022; Kansızoğlu, 2017), the authors employed Hedges' g calculation as a standard measurement value to identify the strength and effectiveness of the relationship between independent and dependent variables (Borenstein et al., 2009). They initially identified relevant statistical data for the studies and then created a Microsoft Excel sheet™ to easily copy them into Comprehensive Meta-Analysis (CMA V2.2™) software. They exploited the following statistical data to calculate Hedges' g value:

- 20 studies included mean scores, standard deviations, and sample sizes for the experimental and control groups.
- 3 studies provided mean scores, sample sizes for the experimental and control groups and independent groups t-value.
- 3 studies contained mean scores, and sample sizes of the experimental and control groups and independent groups' p-values.

Table 1 Characteristics of the studies included in the meta-analysis

Characteristics	Criteria	Studies	f
Publication year	2006–2010	Adesoji and Ibraheem (2009), Balcı (2006), Çalik et al. (2010), Kıngır and Geban (2012), Koç (2009), Olakanmi (2008)	6
	2011–2015	Cakmakci and Aydogdu (2011), Çetin (2014), Demircioğlu and Yadigaroğlu (2011), Kaya (2011), Kurt and Ayas (2012), Odongo (2013), Olakanmi (2015), Taştan Kırık and Boz (2012), Yalçınkaya et al. (2012)	9
	2016–2020	Gongden et al. (2019), Karpudevan and Mathanasegaran (2018), Muchtar et al. (2020), Olakanmi (2017), Olakanmi and Gumbo (2017), Setyovati and Louise (2018), Tsegaye et al. (2020)	7
	2021+	Çubukçu (2023), Fernando and Mahanama (2021), Handayani et al. (2021), Murni et al. (2022)	4
Publication type	Article	Adesoji and Ibraheem (2009), Cakmakci and Aydogdu (2011), Çalik et al. (2010), Çetin (2014), Demircioğlu and Yadigaroğlu (2011), Fernando and Mahanama (2021), Gongden et al. (2019), Handayani et al. (2021), Karpudevan and Mathanasegaran (2018), Kıngır and Geban (2012), Kurt and Ayas (2012), Murni et al. (2022), Olakanmi (2015), Olakanmi (2017), Olakanmi and Gumbo (2017), Taştan Kırık and Boz (2012), Yalçınkaya et al. (2012), Tsegaye et al. (2020)	18
	Dissertation	Balcı (2006), Çubukçu (2023), Kaya (2011), Koç (2009), Odongo (2013), Olakanmi (2008)	6
	Proceedings	Muchtar et al. (2020), Setyovati and Louise (2018)	2
Sample size	1–30	Fernando and Mahanama (2021), Olakanmi (2008)	2
	31–100	Balcı (2006), Cakmakci and Aydogdu (2011), Çalik et al. (2010), Çubukçu (2023), Demircioğlu and Yadigaroğlu (2011), Gongden et al. (2019), Handayani et al. (2021), Karpudevan and Mathanasegaran (2018), Kaya (2011), Kıngır and Geban (2012), Kurt and Ayas (2012), Muchtar et al. (2020), Olakanmi (2015), Olakanmi (2017), Olakanmi and Gumbo (2017), Setyovati and Louise (2018), Tsegaye et al. (2020),Yalçınkaya et al. (2012)	18
	101–300	Adesoji and Ibraheem (2009), Çetin (2014), Koç (2009), Murni et al. (2022), Odongo (2013), Taştan Kırık and Boz (2012)	6

Table 1 (continued)

Characteristics	Criteria	Studies	f
Grade	High school	Adesoji and Ibraheem (2009), Balcı (2006), Çalik et al. (2010), Demircioğlu and Yadigaroğlu (2011), Fernando and Mahanama (2021), Gongden et al. (2019), Handayani et al. (2021), Karpudevan and Mathanasegaran (2018), Kaya (2011), Kıngır and Geban (2012), Kurt and Ayas (2012), Murni et al. (2022), Odongo (2013), Olakanmi (2008), Olakanmi (2015), Olakanmi (2017), Olakanmi and Gumbo (2017), Setyovati and Louise (2018), Taştan Kırık and Boz (2012), Tsegaye et al. (2020), Yalçınkaya et al. (2012)	21
	University	Cakmakci and Aydogdu (2011), Çetin (2014), Çubukçu (2023), Koç (2009), Muchtar et al. (2020)	5
Implementation duration	Short-term (from one week to four weeks)	Balcı (2006), Cakmakci and Aydogdu (2011), Çalik et al. (2010), Çetin (2014), Demircioğlu and Yadigaroğlu (2011), Gongden et al. (2019), Karpudevan and Mathanasegaran (2018), Kaya (2011) Kıngır and Geban (2012), Koç (2009), Kurt and Ayas (2012), Murni et al. (2022), Olakanmi (2015), Olakanmi (2008), Olakanmi (2017), Olakanmi and Gumbo (2017)	16
	Medium-term (from five weeks to eight weeks)	Adesoji and Ibraheem (2009), Çubukçu (2023), Odongo (2013), Taştan Kırık and Boz (2012), Tsegaye et al. (2020), Yalçınkaya et al. (2012)	6
	Long-term (nine weeks and above)	-	
	Unspecified	Fernando and Mahanama (2021), Handayani et al. (2021), Muchtar et al. (2020), Setyowati and Louise (2018)	4

Table 1 (continued)

Characteristics	Criteria		Studies	f
Type of intervention	Enriched learning environment with different techniques		Balcı (2006), Çalik et al. (2010), Çubukçu (2023), Demircioğlu and Yadigaroğlu (2011), Kaya (2011), Kıngır and Geban (2012), Kurt and Ayas (2012), Murni et al. (2022), Odongo (2013), Olakanmi (2017)	10
	Cooperative learning		Adesoji and Ibraheem (2009), Gongden et al. (2019), Koç (2009), Taştan Kırık and Boz (2012)	4
	Computer-assisted instruction		Fernando and Mahanama (2021), Muchtar et al. (2020), Olakanmi (2008), Olakanmi (2015)	4
	Inquiry-based learning		Cakmakci and Aydogdu (2011), Çetin (2014), Yalçınkaya et al. (2012)	3
	Other	Pocket book	Handayani et al. (2021)	5
		Self-regulated learning	Olakanmi and Gumbo (2017)	
		Paradigm of reflective pedagogy	Setyowati and Louise (2018)	
		Context-based learning	Karpudewan and Mathanasegaran (2018)	
		Conceptual change	Tsegaye et al. (2020)	
Prioritized educative arguments	Features of the intervention type (e.g., student engagement, interaction, collaborative work and a combination of different learning techniques) play a significant role at student learning of chemical kinetics		Adesoji and Ibraheem (2009), Aydoğdu (2011), Balcı (2006), Çalik et al. (2010), Çetin (2014), Çubukçu (2023), Demircioğlu and Yadigaroğlu (2011), Fernando and Mahanama (2021), Gongden et al. (2019), Handayani et al. (2021), Karpudevan and Mathanasegaran (2018), Kaya (2011), Kıngır and Geban (2012), Koç (2009), Kurt and Ayas (2012), Muchtar et al. (2020), Murni et al. (2022), Odongo (2013), Olakanmi (2008), Olakanmi (2015, 2017), Olakanmi and Gumbo (2017), Setyovati and Louise (2018), Taştan Kırık and Boz (2012), Tsegaye et al. (2020), Yalçınkaya et al. (2012)	26
	Students' ability to use mathematical models and tools influences their academic performance of chemical kinetics		Adesoji and Ibraheem (2009), Kaya (2011)	2
	Properties of the sample (e.g., composition of the university cohorts) has a pivotal role at facilitating students' learning of chemical kinetics		Cakmakci and Aydogdu (2011), Çetin (2014), Çubukçu (2023), Koç (2009), Muchtar et al. (2020)	5

Meta-analysis Model

The current meta-analysis chose the random effects model for all statistical processes (e.g., calculating the effect-sizes and comparing them with each other or moderator variables) in that it collected the intervention studies from the related literature as the corpus of data and strived to generalize its findings (Borenstein, 2019). Thus, it acknowledged the assumptions and nature of the random-effects model that true effect may be varied from study to study and significant variability between studies is based on interventions, educational levels and differences in samples (Borenstein, 2019; Higgins et al., 2003). Also, the essential values and tests of heterogeneity (e.g., Q-value and I^2 test) (see Table S2 in Supplementary Material) advocated this selection to count up effect-sizes through Comprehensive Meta-Analysis (CMA V2.2™) software (Borenstein et al., 2009; Karadag, 2020). Moreover, educational level, type of intervention and implementation duration were defined as moderator variables to answer the second research question. Because the topics 'chemical kinetics' are taught at different grades in regard to science curricula and national contexts, e.g., grade 9 in UK (e.g., Olakanmi, 2008), grades 10 and 11 in Türkiye (e.g., Çalik et al., 2010; Kıngır & Geban, 2012), grade 11 in Indonesia (e.g., Handayani et al., 2021) and grade 13 in Sri Lanka (Fernando & Mahanama, 2021), the authors decided to merge them under "high school (grades 9–13)" to make them comparable. In a parallel with this decision, the authors preferred "university (undergraduate or bachelor)" to year of study (e.g., freshman or first-year) because some of the studies did not report year of study or educational programme (e.g., Muchtar et al., 2020). Likewise, the implementation durations of the studies under investigation ranged from one week to seven weeks. Given the variation of implementation duration, the authors decided to recruit three categories (short-term from one week to four weeks; medium-term from five weeks to eight weeks; and long-term from nine weeks and above) to easily categorize them in a standard manner and make them comparable with each other. Also, based on the different intervention types and their descriptions adapted from Çalik et al. (2023, 2024), they labelled the studies as the enriched learning environment with different techniques, cooperative learning, computer-assisted instruction, inquiry-based learning, context-based learning, conceptual change and so forth to yield 'type of intervention' moderator variable.

Publication bias: Analysis and Findings

As seen from Fig. 2, there was a symmetrical structure in terms of the relationship between standard error and effect size (Karadag, 2020). As well as no publication bias in the funnel plot (see Fig. 2), the findings of Duval and Tweedie's trim-and-fill test also showed no difference between the observed and adjusted values that need to be tolerated for the effect of the publication bias (see Table S3 in Supplementary Material). This proved that the papers on each side of the centerline was symmetrical (Karadag, 2020). What is more, the findings of Classic fail-safe N and Orwin's fail-safe N values for publication bias indicated that these values (Classic fail-safe $N=3184$; Orwin's fail-safe $=213$) are very high to make the mean effect of

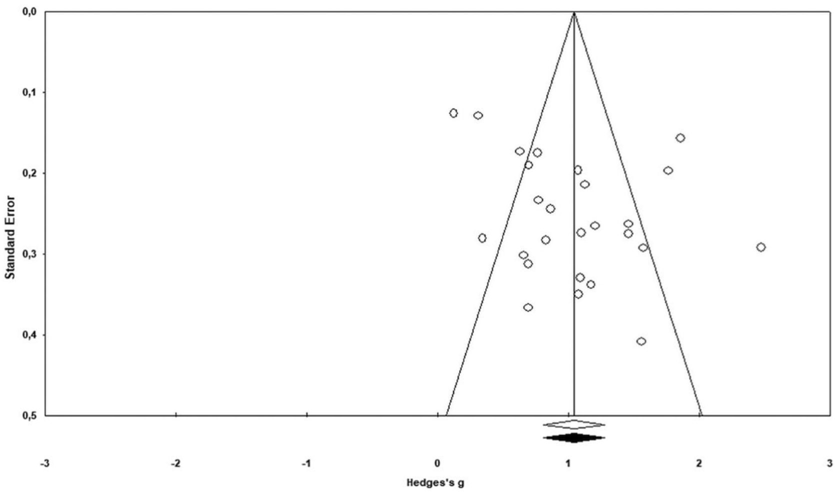

Fig. 2 Funnel plot of standard error by effect-size

this meta-analysis as trivial (see Tables S4-5 in Supplementary Material) (Üstün & Eryılmaz, 2014). In other words, much more additional studies with non-significant findings are needed to nullify the effect of the interventions on academic performance. In addition, the authors calculated the ratio suggested by Mullen et al. (2001) to further examine the publication bias via the formula [N/(5k + 10)] (k = the total number of the studies in the meta-analysis). This ratio was found to be 22.74, which is higher than 1.00 offered as the cut-off point (Mullen et al., 2001). This means that data selection process of the current meta-analysis was highly good and did not possess any publication bias. Finally, the aforementioned values prove that the current meta-analysis had no evidence of publication bias for the corpus of the data.

Findings

The following criteria were utilized to interpret the effect-size values: 0.14 and below (negligible); 0.15–0.39 (low); 0.40–0.74 (medium); 0.75–1.09 (large); 1.10–1.44 (very large); and 1.45 and above (perfectly huge) (Güler et al., 2022).

The Overall Impact of the Interventions on Academic Performance

As can be seen from Table 2, while 23 of them were significant ($p < .05$), three of them were non-significant ($p > .05$) (see Table S6 for stem-and-leaf plot and Figure S1 for forest plot in Supplementary Material). Of these effect-sizes, only one was classified beneath the negligible effect (Güler et al., 2022). The frequencies of low and medium effects were two and five, whilst those for large, very large and perfectly huge effects were seven, four and seven respectively. Also, the overall effect-size for the random-effects model (Hedges' g = 1.042) was labelled under the large effect.

Table 2 The summary of the essential findings in the meta-analysis

Studies	Hedges' g	Standard Error	*P*-value
Adesoji and Ibraheem (2009)	0.125	0.126	0.319
Balcı (2006)	0.694	0.312	0.026
Cakmakci and Aydogdu (2011)	2.475	0.292	0.000
Çalik et al. (2010)	1.462	0.263	0.000
Cetin (2014)	0.699	0.190	0.000
Çubukcu (2023)	1.175	0.338	0.001
Demircioğlu and Yadigaroğlu (2011)	1.077	0.350	0.002
Fernando and Mahanama (2021)	0.697	0.366	0.057
Gongden et al. (2019)	0.775	0.233	0.001
Handayani et al. (2021)	1.573	0.293	0.000
Karpudevan and Mathanasegaran (2018)	1.129	0.214	0.000
Kaya (2011)	0.764	0.175	0.000
Kıngır and Geban (2012)	0.660	0.302	0.029
Koç (2009)	1.767	0.197	0.000
Kurt and Ayas (2012)	1.090	0.329	0.001
Muchtar et al. (2020)	0.343	0.281	0.221
Murni et al. (2022)	0.633	0.173	0.000
Odongo (2013)	1.858	0.156	0.000
Olakanmi (2008)	1.561	0.408	0.000
Olakanmi (2015)	1.204	0.265	0.000
Olakanmi (2017)	1.460	0.274	0.000
Olakanmi and Gumbo (2017)	1.098	0.274	0.000
Setyowati and Louise (2018)	0.310	0.129	0.016
Taştan Kırık and Boz (2012)	1.076	0.196	0.000
Tsegaye et al. (2020)	0.865	0.244	0.000
Yalçınkaya et al. (2012)	0.830	0.283	0.003
Random	1.042	0.119	0.000

The Findings of Statistical Differences between Moderator Variables (Educational Level, Implementation Duration and Type of Intervention)

As can be seen from Table 3, there were no significant difference between the mean effect-sizes of moderator variables (Q-value = 0.637; df = 1; $p > .05$ for educational level; Q-value = 0.20948; df = 1; $p > .05$ for implementation duration; Q-value = 0.64710; df = 3; $p > .05$ for intervention types). This means that all moderator variables did not impact the students' academic performance as a result of the interventions.

The Findings of Descriptive Differences of Individual Moderator Levels

As seen from Table 3, the mean effect-size of university (Hedges' g = 1.289) was higher than that for high school (Hedges' g = 0.981). These values fell into large and very large effects, respectively in regard to Güler et al.'s (2022) classification. Additionally, the mean effect-size for short-term intervention (Hedges' g = 1.142) was higher than that for medium one (Hedges' g = 0.985). Also, these values were labelled very large and large effects respectively. Particularly, the mean effect-size for inquiry-based learning (Hedges' g = 1.322) was the highest value among the intervention types. Similarly, the mean effect-size for the enriched learning environment with different techniques (Hedges' g = 1.094) was higher than those for computer-assisted instruction (Hedges' g = 0.923) and cooperative learning (Hedges' g = 0.929). Whilst the value of inquiry-based learning was categorized under a very large effect, the rest of them fell into a large effect.

Discussion

The overall effect size of the interventions teaching chemical kinetics (Hedges g = 1.042) points a large effect (see Table 2 and Figure S1 in Supplementary Material). This means that they are more effective in improving students' academic performance than the traditional or existing instruction. This supports previous arguments on alternative pedagogical approaches as compared with the traditional or existing instruction (Ahmad et al., 2023; Bain & Towns, 2016; Çalik et al., 2024). However, a broad range of the effect size from 0.125 to 2.475 is related to the nature of experimental design. That is, this variation may result from controlled (i.e. implementation duration and preferred intervention type) or uncontrolled variables (i.e. preparedness level, pre-requests of learning, and cultural context) in any experimental setting. For instance, Adesoji and Ibraheem (2009), who had the lowest effect-size in the current meta-analysis, depicted that students' mathematical background acts as a pre-request for learning chemical kinetics. This shows the importance of mathematical background (as students' preparedness level and pre-requests of learning chemical kinetics) in their own intervention (Bain & Towns, 2016). Also, this proves that the use of mathematical models or tools (e.g., graphs and formulas) in chemical kinetics plays a significant role at accomplishing multi-dimensional framework of chemistry (Bain & Towns, 2016; Talanquer, 2011). Likewise, Muchtar et al. (2020), who reported a low effect, stated such instructional problems as students' familiarity with the subject and lack of facilities like instructional materials and media to learn outside the classroom. This means that uncontrolled variables seem to have undermined the effectiveness of their intervention in improving students' academic performance. Cakmakci and Aydogdu (2011), who possessed the highest effect-size, used evidence from educational theories and research data, clarified related concepts, took into consideration of the students' alternative conceptions and the goals of chemical kinetics and developed appropriate instructional materials to achieve better conceptual understanding. This means that a well-planned intervention has resulted in a better effect-size or increased its effectiveness in improving students' academic performance. Namely, key issues underpinning the nature of an effective intervention should be understood to accomplish the related goals or learning outcomes in particular domains (e.g., academic performance) (Cakmakci & Aydogdu, 2011).

Table 3 The findings of moderator analysis

Moderator variables		k	Point estimate	Standard error	Confidence interval (95%)		Z-value	p-value	Q-value	df (Q)	p-value
					Lower limit	Upper limit					
Educational level	High school	21	0.981	0.122	0.742	1.220	8.049	0.000			
	University	5	1.289	0.366	0.572	2.006	3.523	0.003			
	Total between								0.637	1	0.425
Implementation duration[a]	Short-term	16	1.142	0.125	0.898	1.387	9.148	0.000			
	Medium-term	6	0.985	0.321	0.356	1.614	3.069	0.002			
	Total between								0.209	1	0.647
Type of intervention[b]	Enriched learning environment with different techniques	10	1.094	0.168	0.765	1.423	6.524	0.000			
	Computer-assisted instruction	4	0.923	0.267	0.399	1.446	3.456	0.001			
	Cooperative learning	4	0.929	0.386	0.171	1.686	2.403	0.016			
	Inquiry-based learning	3	1.322	0.541	0.262	2.382	2.444	0.015			
	Total between								0.647	3	0.886

a ‘Unspecified’ category (N=4) was omitted since it did not clearly address the implementation duration.

b Other (N = 5) was disregarded since this category only included one each paper from pocket book, self-regulated learning, paradigm of reflective pedagogy, context-based learning and conceptual change.

The Effects of Moderator Variables on Academic Performance

The findings of the moderator variables revealed non-significant differences at affecting the students' academic performance (see Table 3). This means that moderator variables do not play a significant role in estimating the students' academic performance along with the interventions. This may result from similar or close effect-sizes of the groups within moderator variables. Meanwhile, non-significant difference between the educational levels may come from the small number of the studies with university level or undergraduate students (Bain & Towns, 2016). A similar case is also valid for the implementation duration since only six studies conducted medium-term interventions (k = 6) (see Table 3). Interestingly, the current meta-analysis did not find any study with long-term intervention. This may stem from the scope and content of the topic 'chemical kinetics' suggested by chemistry curricula. As a matter of fact, Bain and Towns (2016) emphasized that some chemistry curricula do not have a primary focus on chemical kinetics. That is, they typically handle it within chemical equilibrium or thermodynamics. Such an inclination may have prevented conducting long-term term interventions. Non-significant difference between the intervention types (see Table 3) indicates that they have similar effects on students' academic performance through the interventions. Further, this result may be seen as an indicator of effectiveness of any alternative pedagogy or intervention vis-à-vis the traditional or existing instruction (Bain & Towns, 2016; Kiryak & Çalik, 2018).

Descriptive Differences between Moderator Variables

The mean effect-size of university level (k = 5) was higher than that of high school (k = 21) and had a better effect-size classification (very large effect) than high school (large effect). This may be explained with the sample of the related studies, for example, pre-service chemistry teachers (Muchtar et al., 2020) or pre-service science teachers (Cakmakci & Aydogdu, 2011; Çetin, 2014; Koç, 2009), who had already passed a high-stake nationwide exam and were familiar with the topic due to their chemistry education at high school. This means that they may have already had proper pre-requests to conceptually comprehend the topic 'chemical kinetics'. For example, its nature requires students to possess mathematical skills (e.g., mathematical modelling and operations) to achieve better academic performance. Namely, mathematical knowledge and skills plays a crucial role in assisting students in understanding chemical kinetics (Adesoji & Ibraheem, 2009; Bain & Towns, 2016). Furthermore, a higher effect-size of university level may result from factors such as greater understanding of mathematics acquired by the time of university instruction or contextually thinking abilities that enable students to link their observations with theoretical aspects (e.g., sub-microscopic and symbolic) of chemistry (Cakmakci et al., 2006; Johnstone, 1991; Taber, 2013; Talanquer, 2011).

Interestingly, the mean effect-size of short-term intervention (Hedges' g = 1.142) was higher than that for medium one (Hedges' g = 0.985) and categorically possessed a different classification (very large effect) from medium one (large effect).

This may come from duration difference between pre- and post-test. Namely, after a short-term intervention, the students may have easily recalled and explained what they have learned. Thus, such a process may have increased their learning possibilities and gains as compared with a medium-term intervention. Phrased differently, an increase in the implementation duration may have reduced the students' interest in learning the topic 'chemical kinetics' or made the intervention regular over time.

The fact that inquiry-based learning (k = 3) (Hedges' g = 1.322) had the highest effect-size value and the best effect-size classification (very large effect) amongst the intervention types may result from its characteristics such as student engagement, stimulating learning curiosity, inquiring about related concepts in the light of evidence, and doing science and scientific research alike scientists (Çalik et al., 2015, 2023, 2024; Orosz et al., 2023). This means that the characteristics of inquiry-based learning seem to have matched with the nature or framework of the topic 'chemical kinetics'.

Even though computer-assisted instruction has the power to represent macroscopic, sub-microscopic, and symbolic aspects of chemistry via the topic 'chemical kinetics,' it had the lowest effect-size on academic performance (Fernando & Mahanama, 2021; Muchtar et al., 2020; Olakanmi, 2008; Olakanmi, 2015). This may stem from the implementation procedure or preferred computer-assisted tools (e.g., MS Excel worksheet, Android application and web-based simulations). For example, although social interaction, collaboration and group work are important to build knowledge along with computer-assisted instruction (Chen et al., 2018), some studies may have prioritized individual learning tasks in their interventions, e.g., working through a computer simulation and writing their gained learning on the related form or box. Thus, they may have provided limited social interaction and discussion with peers and teachers to share what they have learned and made inferences. This means that the use of computer-assisted instruction in learning the topic 'chemical kinetics' needs to create strong in-class interactions. As a matter of fact, higher effect-sizes of the enriched learning environments with different techniques, which offer strong in-class interactions and discussions by integrating computer-assisted tools into other instructional approaches, models or strategies, support this argument (Çalik et al., 2010; Kurt & Ayas, 2012; Odongo, 2013). Moreover, this may also stem from the assessment tools. For example, Olakanmi (2008), who had the highest effect-size value for computer-assisted instruction, administered a three-part test, which asked the students to choose the correct answer from the options (multiple-choice questions), match statements with each other and predict how the factors affect the rate of reaction. Thereby, students may have easily chosen or guessed their answers as compared with open-ended or conceptual questions. In fact, this may result from limited facilities of technological tools or students' familiarity with computer-assisted instruction or newly developed computer-based tools. For instance, three of these studies were implemented in Indonesia (Muchtar et al., 2020) (Hedges g = 0.343), Sri Lanka (Fernando & Mahanama, 2021) (Hedges' g = 0.697) and Nigeria (Olakanmi, 2015) (Hedges' g = 1.204), which are developing countries, whilst one study (Olakanmi, 2008) (with the highest effect-size value for this group) was carried out in the UK (as a developed country) as a master's thesis. This variation may also come from the publication type, e.g., dissertation

(Olakanmi, 2008) supervised by a scientific committee, peer-reviewed journals (Fernando & Mahanama, 2021; Olakanmi, 2015) and proceedings (Muchtar et al., 2020). That is, the proceeding had the lowest effect-size value for the group (computer-assisted instruction).

The large effect-size of the enriched learning environment with different techniques (k = 10) may result from an enthusiasm prioritizing a combined advantage or potential of different methods (e.g., conceptual change text, analogy, demonstration, and hands-on activities/laboratory) (Balcı, 2006; Çalik et al., 2010; Kaya, 2011; Kıngır & Geban, 2012; Murni et al., 2022; Olakanmi, 2017). Thus, the studies in this group seem to have enriched learning environment to meet various learning styles and pose students' capacities of learning (Çalik et al., 2010; Çalik et al., 2023). Given the relevant effect-size, this goal seems to have been accomplished to some extent.

Even though the mean effect-size of cooperative learning (k = 4) pointed to a large effect, the effect-sizes of the studies in this group were varied and ranged from 0.125 (Adesoji & Ibraheem, 2009) to 1.767 (Koç, 2009). This means that some of them seem to have well associated the nature and/or multi-dimensional framework of the topic 'chemical kinetics' (e.g., experiences, models, and visualizations of chemistry knowledge) with features of cooperative learning (e.g., positive interdependence, accountability, promotive interactions, teaching interpersonal skills and group processing) (Bain & Towns, 2016; Johnson et al., 1998; Rahman & Lewis, 2020; Talanquer, 2011). In other words, the use of cooperative learning needs a well-designed intervention that pays more attention to its core dynamics to result in better chemistry learning and academic performance. To sum up, type of intervention as a moderator variable, especially cooperative learning (k = 4) and computer-assisted instruction (k = 4), is somewhat effective in developing chemical kinetics-based academic performance.

Conclusion and Implications

The mean effect-size of this meta-analysis offers that the interventions are more effective and fruitful in improving the students' academic performance than the traditional or existing instruction. Also, a broad range of the effect sizes (from 0.125 to 2.475) indicates that any experimental study should be well-planned and implemented based on controlled and uncontrolled variables. Given non-significant differences for the effects of moderator variables (implementation duration, type of intervention and education level) on academic performance, it can be inferred that they do not play a significant role in estimating the students' academic performance through the interventions. However, the categorical differences between individual moderator levels point to the role of these moderator variables in predicting their academic performance along with the interventions. In fact, this interpretation difference between statistical and descriptive findings of the mean effect-sizes indicates the importance of a combined assessment. Since mathematical knowledge and skills are important in learning the topic 'chemical kinetics', teachers or practitioners should initially measure students' competencies of mathematics and then develop their lesson plans or sequences. In fact, such a case sheds more light on the importance of STEM education that calls chemistry and mathematics teachers for collaboratively working to attain a sound and contextual understanding of the topic ‘chemical kinetics’. Furthermore, to get more insights about the effectiveness of short- or medium-term interventions, future research may consider administering successive data collection tools (e.g., weekly quizzes, observation forms, homework and self-assessment) as well as post-test (Şenel Çoruhlu et al., 2023). The categories (large and very large effects) for the mean-effect sizes of the moderator variables suggest that the interventions would be productive or contain strong effects across the studies (Çalik et al., 2024).

Future research may use different variables such as assessment tools or types, countries or publication type to test whether they act as significant moderator variables to estimate students’ academic performance. Taking into consideration of the mean-effect size of inquiry-based learning, it can be deduced that the characteristics of inquiry-based learning overlap with the nature or framework of the topic ‘chemical kinetics’. This means that it is the best matched approach to teach this topic. Needless to say that the limited number of the studies for some categories (e.g., university level, cooperative learning, computer-assisted instruction, inquiry-based learning, medium-term intervention) has restricted further interpretation of the relevant findings. In a similar vein, the lack of studies with a long-term intervention stands as a gap in the current literature. Thereon, future research should explore whether an increase in implementation duration will result in better academic performance. Similarly, since the current study reported some extreme values for the interventions, future research should qualitatively investigate their implementation processes, lesson sequences and assessment tools in depth.

Limitations of the Study

Because the current-meta analysis concentrated on the interventions teaching chemical kinetics and excluded those integrated with chemical equilibrium and thermodynamics, this may be seen as the first limitation of the study. If enough studies become available for these integrated topics, future studies can meta-analytically evaluate how separate and integrated topics influence students’ academic performance. Likewise, since this study covered English and Turkish as publication languages, disregarding other languages may be viewed as the second limitation of the study. Future research may include these languages and compare their results with the current meta-analysis. Also, the current meta-analysis principally focused on easily distinguishable, measurable, comparable, and controlled moderator variables (type of intervention, implementation duration and educational level) and did not handle hardly detectable, comparable, and uncontrolled ones (e.g., students’ ability to use mathematical models and tools, composition of the university cohorts, and studies’ characteristics for different cultures and contexts). This may be viewed as the third limitation of the study. Lastly, the quantitative nature of the meta-analysis may be seen as the fourth limitation of the study. Therefore, future research may qualitatively elaborate the findings of the current meta-analysis.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10763-024-10523-w.

Funding Not applicable.

Data Availability The datasets analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical Statement All procedures performed in this study followed the ethical standards of the Department of Health Standards on Human Research (DOH/QD/SD/HSR/0.9) and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Disclosure Statement Since Muammer Çalık serves as the Senior Editor of this journal, Prof. Dr. David F. Treagust handled this manuscript to mitigate this conflict of interest, and was responsible for all decision making.

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