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Developing a Mathematics Instructional Model to Enhance Computational Thinking Skills among Pre-service Mathematics Teachers in Support of the Sustainable Development Goals: A Bibliometric Analysis and Empirical Study

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A B S T R A C T

Computational thinking is essential for preparing future mathematics teachers to address complex problems in digital and sustainable education. This study developed and evaluated a mathematics instructional model for pre-service mathematics teachers using a descriptive bibliometric analysis and an empirical research-and-development approach. Scopus data showed rapid growth in publications on computational thinking from 1987 to 2025, confirming its increasing educational relevance. The model comprised six stages: situation presentation, analysis, association, synthesis, designing and arranging problem-solving procedures, and conclusion. 30 participants completed a one-group pretest-posttest implementation. Results showed significant improvements in decomposition, pattern recognition, abstraction, and algorithm design, supported by positive interview responses. The model provides a framework for computational thinking development and supports SDG-oriented quality teacher education.

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1. INTRODUCTION

Computational thinking is an essential 21st-century competency that enables learners to decompose complex problems, recognize patterns, identify relevant information, and design systematic solutions. Although initially associated with computer science, computational thinking is increasingly important in mathematics education because it supports mathematical reasoning, problem-solving, and the application of abstract concepts to authentic situations (Wing, 2006; Weintrop *et al.*, 2016; Kallia *et al.*, 2021). Its main dimensions (*i.e.,* decomposition, pattern recognition, abstraction, and algorithm design) help learners organize information and construct logical solution procedures (Cui and Ng, 2021; Maharani *et al.*, 2021; Subramaniam *et al.*, 2022).

The development of education is relevant to the Sustainable Development Goals (SDGs) (Maryanti *et al.*, 2022). Future teachers are expected to design active, inclusive, technology-supported, and problem-oriented learning environments. Computational thinking can therefore support sustainable education by preparing teachers and learners to address complex problems through logical reasoning, collaboration, and evidence-based decision-making.

Education systems, including Thailand, are shifting from knowledge transmission toward competency-based and learner-centered education (Fry and Bi, 2013). Current reforms emphasize critical thinking, problem-solving, innovation, digital literacy, and the application of knowledge in real-life contexts (Fauzi *et al.*, 2024). Computational thinking has also been incorporated into Thai educational policies and curricula as an important component of systematic problem-solving (Ersozlu *et al.*, 2023). However, its effective implementation depends strongly on teachers' ability to integrate mathematical content, pedagogy, technology, and computational thinking into classroom instruction (Yadav *et al.*, 2017; Kite *et al.*, 2021; Rodrigues *et al.*, 2024; Yun and Crippen, 2025).

This challenge is particularly important for pre-service mathematics teachers, who must master abstract mathematical content while learning how to transform it into meaningful instructional activities. Previous studies have reported moderate computational thinking competence and limited confidence among pre-service teachers in integrating it into discipline-specific teaching (Hamed *et al.*, 2024; Haşlaman *et al.*, 2024). Existing studies also tend to focus on programming, coding, and school-level education, whereas applications in higher mathematics and pre-service mathematics teacher education remain limited (Katchapakirin *et al.*, 2022; Philuek *et al.*, 2025).

An effective instructional model should therefore connect computational thinking with authentic mathematical problems, meaningful learning, collaborative inquiry, and systematic reflection (Vallori, 2014). Bibliometric analysis can complement this development by mapping the global growth, influential publications, research themes, and conceptual structure of computational thinking research. Using "computational thinking" as the main search term provides a broad overview of the field and helps position mathematics teacher education within its wider research landscape.

This study aimed to map computational thinking research through bibliometric analysis, develop and validate a mathematics instructional model, and empirically examine its effects on pre-service mathematics teachers' computational thinking skills and perceptions. The novelty of this study lies in integrating broad bibliometric evidence, instructional model development, classroom implementation, and the SDGs into a single research framework.

2. METHODOLOGY

This study combined bibliometric analysis with a research and development approach. The bibliometric component examined the development and intellectual structure of computational thinking research, while the empirical component involved model development, expert validation, and classroom implementation. Bibliographic records were retrieved from Scopus using the search term “computational thinking” in the title, abstract, and keywords. The bibliometric findings were used to identify dominant research themes and gaps related to mathematics education, teacher preparation, and the SDGs.

The instructional model was developed as a synthesis of computational thinking, constructivism, meaningful learning, problem-based learning, and collaborative learning. The model comprised objectives and assumptions, instructional syntax, social system, principles of reaction, support system, and application. Its 6 instructional stages were situation presentation, analysis, association, synthesis, designing and arranging problem-solving procedures, and conclusion. 7 experts evaluated the model, 6 lesson plans, the computational thinking test, and the interview form. The lesson plans covered analytic geometry and were implemented for 18 hours.

The population comprised 90 pre-service mathematics teachers enrolled in an Analytic Geometry course at Nakhon Ratchasima Rajabhat University. One class of 30 students was selected through cluster random sampling, and 15 students were randomly selected for interviews. A one-group pretest-posttest design was employed. Participants completed the pretest, followed by 6 instructional units, and then completed the posttest. Because the data were not normally distributed, the Wilcoxon signed-rank test was used to compare pretest and posttest scores.

3. RESULTS AND DISCUSSION

The Scopus search identified 7,862 documents published between 1987 and 2025 (**Figure 1**). Publication output remained very limited until the mid-2000s, increased gradually after 2008, and grew sharply from approximately 2016 onward. Computational thinking has developed from a relatively specialized concept into a rapidly expanding multidisciplinary research field. The substantial growth during the last decade reflects increasing interest in computational thinking as a key competency in education, mathematics, science, technology, and teacher preparation. The results also support its relevance to the SDGs, particularly SDG 4, because computational thinking promotes problem-solving, digital competence, and future-oriented learning. However, the broad publication growth does not necessarily indicate that computational thinking has been sufficiently integrated into pre-service mathematics teacher education. Much of the existing literature remains associated with programming, coding, and school-level learning, while domain-specific instructional models for future mathematics teachers remain limited (Yadav *et al.*, 2017; Kite *et al.*, 2021; Rodrigues *et al.*, 2024; Yun and Crippen, 2025).

The mathematics instructional model was developed with 6 components: goals and assumptions, instructional syntax, social system, principles of reaction, support system, and application. The complete description of the model is presented in **Table 1**, while the relationships among its components are illustrated in **Figure 2**. The instructional syntax consisted of 6 stages: situation presentation, analysis, association, synthesis, designing and arranging problem-solving procedures, and conclusion.

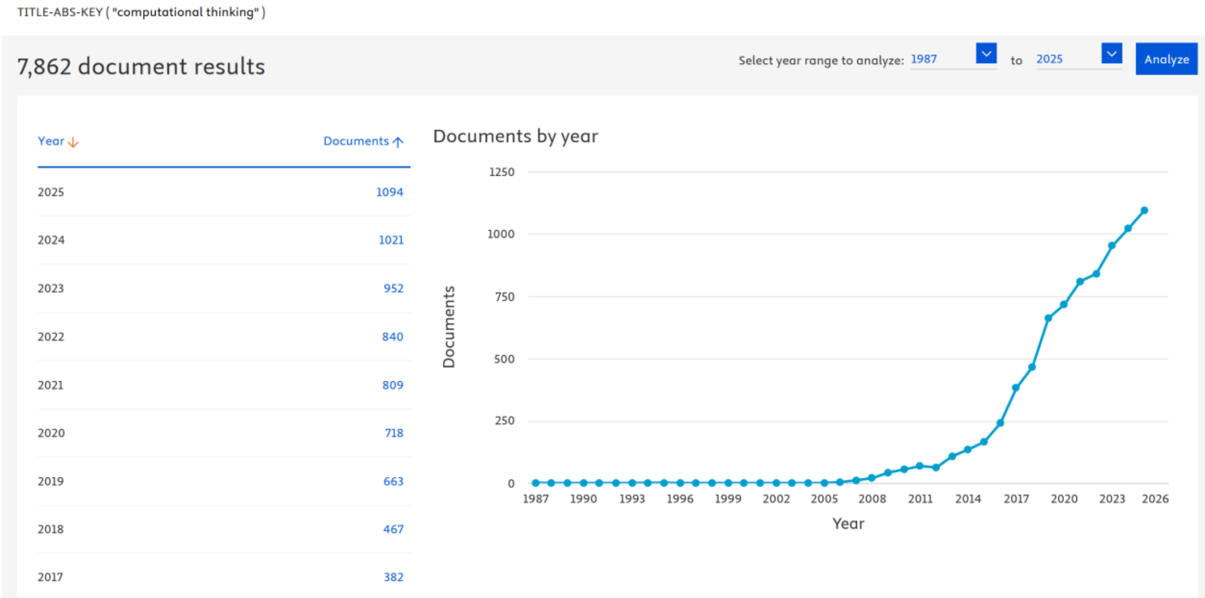

Figure 1. Annual number of Scopus-indexed publications containing the term "computational thinking" from 1987 to 2025. Data were obtained and updated in June 2026.

Table 1. The mathematics instructional model for enhancing computational thinking skills among pre-service mathematics teachers.

COMPONENT	DESCRIPTION
1. Goals and assumptions	The primary goal of the instructional model is to enhance the computational thinking skills of pre-service mathematics teachers through authentic mathematical problem situations and problem-based learning activities. The model assumes that computational thinking can be developed when learners actively analyze problems, connect new information with prior knowledge, construct mathematical understanding collaboratively, and formulate systematic problem-solving procedures.
2. Instructional syntax	Before the instructional process begins, a pretest is administered to assess students' prior knowledge and baseline computational thinking skills. The instructional process consists of 6 sequential stages: situation presentation, analysis, association, synthesis, designing and arranging problem-solving procedures, and conclusion. After all instructional stages have been completed, a posttest is administered to evaluate students' computational thinking development.
Stage 1: Situation presentation	In this stage, the instructor presents an authentic mathematical problem derived from a relevant real-life context. Students are encouraged to examine the problem situation, identify the available information, clarify the expected outcome, and recognize the relationship between the mathematical content and everyday experience. This stage is grounded in Meaningful Learning Theory and Problem-Based Learning, which emphasize connecting new knowledge with prior experience and learning through authentic problem situations.

Table 1 (continue). The mathematics instructional model for enhancing computational thinking skills among pre-service mathematics teachers.

COMPONENT	DESCRIPTION
Stage 2: Analysis	Students analyze the given situation by organizing available information and decomposing the main problem into smaller and more manageable subproblems. They identify known and unknown information, determine the relationships among variables, and discuss possible directions for solving the problem. Students are also encouraged to search for relevant information and construct knowledge independently before sharing their findings with group members. This stage primarily develops decomposition and is supported by Constructivist Theory and Collaborative Learning. The instructor facilitates the process by asking guiding questions, clarifying learning strategies, and providing appropriate support without directly giving the solution.
Stage 3: Association	Students connect newly acquired information with their existing knowledge and previous mathematical experiences. Through discussion and collaborative inquiry, they compare the present problem with previously encountered problems, identify similarities and relationships, and develop possible solution strategies. This stage promotes pattern recognition by helping learners identify recurring mathematical structures. It is grounded in Constructivist Theory, which views learning as an active process of connecting prior knowledge with new experiences. The instructor acts as a facilitator who encourages students to explain their reasoning and evaluate the relevance of their previous knowledge.
Stage 4: Synthesis	Students collaboratively examine, organize, and integrate the information generated during the previous stages. They distinguish essential information from irrelevant details, combine related mathematical ideas, and construct a coherent representation of the problem. The synthesized knowledge is then used as the basis for developing an appropriate solution strategy. This stage primarily strengthens abstraction because students are required to focus on the most relevant features of the problem. Collaborative Learning supports this process by enabling students to compare interpretations and construct shared understanding.
Stage 5: Designing and arranging problem-solving procedures	Students design, articulate, and arrange systematic procedures for solving the problem based on the knowledge and strategies developed in the previous stages. They formulate a logical sequence of mathematical operations, examine the consistency of each step, and discuss alternative procedures with their peers. The proposed procedures are reviewed, verified, and refined before being implemented. This stage primarily develops algorithm design by encouraging students to express their reasoning as an ordered, logical, and reusable procedure. The instructor provides feedback, prompts students to justify each step, and supports the refinement of their solutions.
Stage 6: Conclusion	Students summarize the outcomes of the problem-solving process and reflect on the knowledge and computational thinking skills developed during the activity. They verify their final answers, explain the reasoning underlying their solutions, and consider how the procedures may be applied to other mathematical or real-life problems. Students also share their conclusions with classmates and evaluate alternative approaches. This stage is grounded in Constructivist Theory and Meaningful Learning Theory because learners consolidate new knowledge by connecting it with previous experiences and broader applications. The instructor facilitates reflection and helps students generalize the main principles learned from the activity.

Table 1 (continue). The mathematics instructional model for enhancing computational thinking skills among pre-service mathematics teachers.

COMPONENT	DESCRIPTION
3. Social system	The social system describes the roles and relationships of the instructor and students during the learning process. The instructor presents authentic problem situations, facilitates inquiry, provides guidance, and encourages students to develop their own solutions rather than supplying answers directly. Students are responsible for exploring information, organizing data, decomposing problems, discussing ideas, and constructing conclusions collaboratively. Group interaction is emphasized to promote shared understanding, communication, and collective knowledge construction.
4. Principles of reaction	The instructor observes students' learning activities and responds to their needs by providing appropriate scaffolding, feedback, and positive reinforcement. Guiding questions are used to stimulate deeper thinking and encourage students to justify their reasoning. The instructor also promotes reflective practice by inviting students to discuss the strengths and weaknesses of their problem-solving procedures. Feedback from both the instructor and peers is used to improve students' computational thinking skills and strengthen their confidence in mathematical problem-solving.
5. Support system	The support system includes lesson plans, student worksheets, authentic mathematical problems, internet access, online learning resources, mathematical representations, and appropriate digital or mathematical software. These resources help students search for information, visualize mathematical relationships, compare alternative solutions, communicate ideas, and construct knowledge collaboratively. The selection of supporting resources should be aligned with the mathematical content, students' prior knowledge, and institutional facilities.
6. Application	The instructional model is particularly suitable for mathematical content that involves authentic applications, multiple representations, and systematic solution procedures. Examples include calculating distances between points, determining equations of lines and conic sections, analyzing coordinate relationships, and solving other problems in Analytic Geometry. The model may also be adapted to algebra, calculus, probability, statistics, and other areas of mathematics. Effective implementation requires adjustment to students' developmental levels, prior knowledge, learning objectives, and available technological resources.

The stages were designed to develop the four principal dimensions of computational thinking. Situation presentation introduced an authentic mathematical problem and clarified its context. Analysis supported decomposition by dividing complex problems into smaller components. Association promoted pattern recognition by connecting new information with prior knowledge. Synthesis strengthened abstraction by selecting essential information and constructing mathematical representations. Designing and arranging problem-solving procedures developed algorithm design, while conclusion supported verification, reflection, and generalization. This structure is consistent with constructivism, meaningful learning, problem-based learning, and collaborative learning, which emphasize active knowledge construction through experience and social interaction (Vallori, 2014; Kallia *et al.*, 2021).

The expert evaluation indicated that the model was highly appropriate for implementation, with an overall mean score of 4.66 (SD = 0.48). The 6 lesson plans also received a very high mean score of 4.71 (SD = 0.48). The model was considered theoretically coherent, operationally clear, and suitable for developing computational thinking among pre-service mathematics teachers.

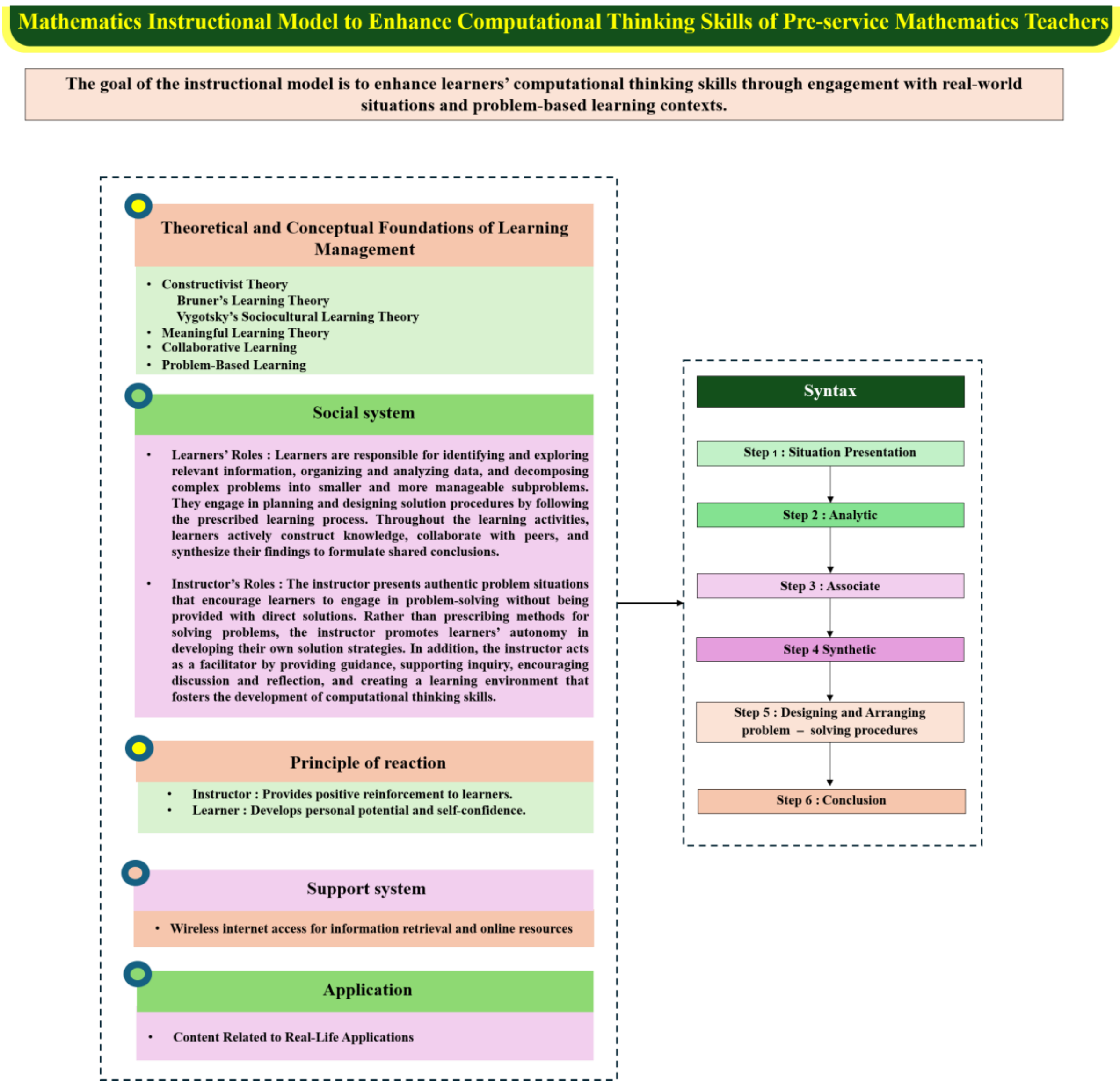

Figure 2. Mathematics instructional model for enhancing computational thinking skills among pre-service mathematics teachers.

The empirical results are presented in **Table 2**. The overall computational thinking score increased from 15.23 (SD = 5.06) before the intervention to 63.60 (SD = 13.77) after the intervention. The Wilcoxon signed-rank test showed a statistically significant difference between the pretest and posttest scores ($Z = 4.79$, $p < 0.001$). The estimated effect size was $r = 0.87$, indicating a large improvement following implementation. However, the result should be interpreted cautiously because the study employed a one-group pretest-posttest design without a control group.

All four dimensions of computational thinking improved after the intervention. The decomposition score increased from 4.00 to 14.97, pattern recognition from 3.97 to 14.97, abstraction from 3.47 to 17.67, and algorithm design from 3.80 to 17.33. Abstraction obtained the highest posttest mean, suggesting that the synthesis stage effectively supported students in distinguishing relevant information from unnecessary details and constructing concise mathematical representations. The high score for algorithm design also indicates that the model helped students arrange logical and sequential problem-solving procedures.

Table 2. Comparison of computational thinking scores before and after the intervention.

COMPUTATIONAL THINKING DIMENSION	MAXIMUM SCORE	N	PRETEST MEAN	PRETEST SD	POSTTEST MEAN	POSTTEST SD	Z	P-VALUE
Decomposition	21	30	4.00	1.84	14.97	3.30	4.79	<0.001
Pattern recognition	21	30	3.97	2.19	14.97	3.32	4.79	<0.001
Abstraction	24	30	3.47	1.36	17.67	3.77	4.79	<0.001
Algorithm design	24	30	3.80	1.65	17.33	4.12	4.79	<0.001
Overall computational thinking	90	30	15.23	5.06	63.60	13.77	4.79	<0.001

Note: Differences between pretest and posttest scores were analyzed using the Wilcoxon signed-rank test. The estimated overall effect size was $r = 0.87$.

Decomposition and pattern recognition produced equal posttest means and remained lower than abstraction and algorithm design. These skills may require repeated exposure to diverse and unfamiliar mathematical situations. Decomposition requires students to identify connected subproblems, while pattern recognition requires comparisons across different mathematical structures. Both dimensions develop progressively through sustained problem-solving experience (Weintrop *et al.*, 2016; Kallia *et al.*, 2021; Subramaniam *et al.*, 2022).

The posttest mean of 63.60 out of 90 was equivalent to 70.67%, slightly above the predetermined criterion of 70%. The group mean reached the expected level, although the margin above the criterion was relatively small. Therefore, the findings should primarily emphasize the significant improvement in computational thinking rather than claiming complete mastery. Reporting the proportion of individual students who achieved the criterion would provide additional evidence regarding instructional effectiveness.

The interview results supported the quantitative findings and produced three major themes. First, students perceived the model as active, collaborative, and problem-oriented. Guiding questions and group activities encouraged them to analyze problems independently rather than rely on direct explanations from the instructor. Second, their ability to decompose problems, recognize relationships, select relevant information, and arrange solution procedures had improved. Third, they expressed greater confidence in applying computational thinking in their future mathematics teaching.

These qualitative findings are important because pre-service mathematics teachers must develop computational thinking both as learners and as future instructional designers. Experiencing the model directly may help them understand how computational thinking can be incorporated into classroom activities. Nevertheless, the participants noted that implementation at the school level should be adjusted to learners' age, prior knowledge, and developmental level, while sufficient time should be provided for group discussion and reflection.

The integration of bibliometric and empirical findings strengthens the contribution of this study. The bibliometric results demonstrate the rapid global expansion of computational thinking research, while the empirical results show how the concept can be operationalized through a structured mathematics instructional model. The study therefore extends computational thinking beyond programming-centered applications and positions it as a mathematical and pedagogical competency for future teachers.

The model also supports the educational direction of the SDGs, particularly SDG 4, by contributing to the preparation of qualified teachers capable of implementing active, problem-based, and future-oriented learning. However, this relationship should be understood as a contribution to SDG-oriented education rather than direct evidence of SDG achievement. Further studies involving control groups, larger samples, multiple institutions, delayed posttests, and observations of teaching practice are needed to confirm the model's long-term effectiveness and transferability.

4. CONCLUSION

This study integrated bibliometric evidence with instructional model development and classroom implementation to strengthen computational thinking among pre-service mathematics teachers. Scopus data showed rapid growth in computational thinking research, confirming its increasing educational relevance. The developed 6-stage model was rated highly appropriate by experts and significantly improved decomposition, pattern recognition, abstraction, and algorithm design. Student interviews also indicated stronger participation, systematic reasoning, collaboration, and confidence for future teaching. These findings support the model's contribution to SDG 4 through future-oriented teacher preparation. Nevertheless, controlled, multi-institutional, and longitudinal studies are required to confirm its effectiveness, transferability, and long-term classroom impact across diverse contexts.

5. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

6. ACKNOWLEDGMENTS

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