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Organizing students' research activities based on STEM elements in the study process

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ABSTRACT

Although science, technology, engineering, and mathematics (STEM) integration in higher education is advancing globally, its adoption in geography programs in Kazakhstan remains limited. This study examines the effectiveness of embedding selected STEM elements into the course "Geography of Aktobe Oblast" as a means of strengthening students' research competencies. A mixed-method design was employed, combining analysis of satellite-derived indicators, work with geospatial platforms (arcGIS Pro, EoSDa Crop Monitoring, and Eo Browser), practical climate-based calculations, classroom observations and comparative assessment analysis. The 24 students participated in the intervention, completing a series of inquiry-driven tasks involving the Normalized Difference Vegetation Index (NDVI) interpretation, spectral reflectance analysis and climatological correlations. Survey data indicated that more than 90% of participants reported improved understanding of environmental processes, while many noted gains in analytical reasoning and data-driven interpretation. Midterm performance results showed a modest but consistent improvement following the implementation of STEM-oriented assignments. The findings suggest that structured integration of geospatial and analytical STEM tools can meaningfully support the development of research skills in university geography courses. By enabling students to work with authentic environmental datasets, the approach cultivates higher-order reasoning, interdisciplinary thinking and sustained learner engagement. The results highlight the potential for broader application of STEM-based instructional models in Kazakhstani higher education and underscore the need for further longitudinal and comparative studies to evaluate long-term impacts.

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1. INTRODUCTION

Strengthening interdisciplinary education has become an essential component of Kazakhstan's national educational strategy, particularly in light of the country's efforts to expand technological competencies and align higher education with global science, technology, engineering, and mathematics (STEM) standards. Recent policy initiatives emphasize the need to integrate digital tools, analytical practices and research skills across university programs [1]. Although STEM education has developed rapidly worldwide, its systematic implementation in Kazakhstan—especially within geography education—remains limited [2]. This creates the need for empirical studies evaluating how STEM-based instructional models function in local university contexts.

In the international literature, STEM approaches are consistently linked to improvements in students' analytical reasoning, research skills, and digital literacy. Scholars highlight that interdisciplinary learning environments stimulate creative and inquiry-oriented competencies, particularly when instruction involves authentic datasets and real-world problem contexts [3], [4]. Similarly, studies from the United States, Europe, and Asia demonstrate that STEM integration contributes to students' conceptual understanding and enhances motivation toward scientific and technological subjects [5], [6].

Geography education is uniquely positioned to adopt STEM approaches because it inherently incorporates spatial reasoning, environmental analysis and digital tool use. Researchers argue that STEM-based geography instruction encourages higher-order thinking by engaging students in problem-solving tasks, modeling, and satellite-data interpretation [7]. Integrating engineering design principles and data-driven inquiry further strengthens learners' ability to analyze real environmental processes [8]. Moreover, STEM-based assessment models have demonstrated their effectiveness in enhancing students' transfer of knowledge across environmental and spatial tasks [9].

In this global context, the introduction of STEM-based teaching elements in Kazakhstan's geography programs is both timely and necessary. Local and international studies indicate that science, technology, engineering, art, math or STEAM- and geographic information systems (GIS)-integrated approaches can modernize the curriculum and improve methodological preparation of future teachers [10], [11]. STEM integration may also support the development of innovative professional competencies, aligning national geographic education with international trends [12], [13].

Despite its relevance, no prior empirical studies in Kazakhstan have evaluated how STEM-based tasks influence university students' research skills within regional geography courses. This study addresses that gap by examining the implementation of STEM-oriented tasks—specifically, the analysis of the Normalized Difference Vegetation Index (NDVI) dynamics, climatological indicators and hydrological datasets—within the course "Geography of Aktobe oblast." The study aims to determine how students respond to STEM-based instruction and to assess whether their analytical and research competencies improve as a result of working with satellite and geospatial data. To achieve this goal, the following research questions were formulated:

i) How do students perceive STEM-based instruction integrated into the course?
ii) Does working with satellite and geospatial data contribute to the improvement of students' analytical and research skills?

2. LITERATURE REVIEW

Foreign researchers emphasize that modern specialists must adhere to the concept of lifelong learning (LLL), continuously developing analytical competence and self-improvement skills to remain competitive in dynamic professional environments [6]. Within this context, Chalmers *et al*. [7] proposed a six-component structural model demonstrating how STEM education can be effectively integrated into STEM instruction. Their work highlights that STEM is not merely a set of separate disciplines, but a unified pedagogical framework that fosters inquiry, reasoning and problem-solving.

The application of STEM and STEAM technologies in natural science education has been examined through design-based learning models. English *et al*. [8] showed that constructing earthquake-resistant building models enhances students' research skills, promotes the use of engineering design principles and strengthens interdisciplinary thinking. Chinese researchers have similarly contributed to the advancement of STEM curricula, Li *et al*. [10] documented reforms at Jinan University, where theoretical STEM concepts were transformed into hands-on practice through structured laboratory platforms. Their findings support the broader global argument that 21st-century STEM instruction must rely on research-based, creativity-oriented learning environments designed to motivate students and cultivate innovation [5].

Comparative studies of STEM implementation in the United States, Korea, and Taiwan demonstrate that high-performing educational systems view STEM as interdisciplinary, practice-oriented learning focused on solving real-world problems [6]. This position aligns with the argument that research skills should be formed through continuous engagement in inquiry tasks, collaborative learning and practical activities that allow students to test hypotheses, analyze evidence and draw reasoned conclusions [7]. Scholars also note that STEM must develop critical thinking, creativity and rational decision-making by enabling learners to work in groups, distribute responsibilities and jointly construct solutions to authentic problems [8].

Kazakh researchers have also begun examining the integration of STEM elements in national educational practice. Laishkhanov *et al*. [14] and Tokpanov *et al*. [15] highlight the methodological importance of incorporating STEM-based research tasks into geography education, noting that these approaches align with Kazakhstan's effort to build a multilevel, internationally competitive educational model. Their work underscores the potential of STEM integration to modernize pedagogical practices, particularly in natural sciences and geography instruction.

Recent publications have addressed the theoretical and methodological challenges associated with STEM education, including issues of effectiveness, curriculum coherence and interdisciplinary alignment [11]–[14]. These studies collectively emphasize that STEM must be systematically embedded into teaching practice rather than implemented through isolated activities. Within geography education, digital platforms such as EoSDa Crop Monitoring provide unique opportunities to enhance students' research skills by allowing them to observe environmental dynamics, analyze satellite imagery and interpret spatial patterns in real time [15].

Interest in STEM education in Kazakhstan has grown significantly in recent years, with the establishment of new STEM laboratories and the adoption of updated curricula designed to enhance students' research competencies [16]. Given the increasing emphasis on technological fluency, integrating STEM elements into geography education has become essential for preparing students to work with complex environmental data and engage in evidence-based decision-making. Consequently, organizing research activities through STEM-oriented tasks represents a critical direction for advancing university-level geography instruction.

3. METHOD

The study was conducted based on a mixed-method quasi-experimental design [11], [12]. The integration of quantitative and qualitative data made it possible to comprehensively assess the impact of STEM on students' research competencies. The study followed a pre–post intervention model and was carried out with a single group; that is, students' learning outcomes were analyzed before and after the implementation of STEM elements. Due to the institutional nature of the study and limitations of the curriculum, a control group was not used. In this regard, to enhance the reliability of the research results, a multi-source triangulation method [7], [8] (observation, survey, academic performance) was applied.

The study involved 24 undergraduate students enrolled in the 6B01506 Geography Educational Program at K. Zhubanov Aktobe Regional University, Republic of Kazakhstan. Participants were selected using purposive sampling based on the following criteria: being fourth-year students; studying the course "Geography of Aktobe Oblast"; and having an initial level of experience in working with GIS. Participation in the study was voluntary, and the research results did not affect the students' academic performance. All participants were informed about the purpose of the study, the procedures involved, and data confidentiality. Students' research skills were considered in this study as a multi-component construct. The key research skills formed through STEM included the following competencies: digital and geospatial literacy, analytical interpretation skills, evidence-based reasoning, interdisciplinary thinking, and research autonomy. The assessment of students' research competencies was carried out according to the directions presented as in Figure 1.

During the study, STEM-based instruction was implemented over a 15-week instructional cycle. Practical classes were conducted in the university's innovative tourism laboratory. Within the scope of the study, in order to develop data-driven research activities, students worked with real satellite data and completed the following tasks [3], [5], [15], [17]: analysis of seasonal vegetation dynamics using NDVI indicators; calculation and comparison of climatic data (temperature, precipitation, evaporation); modeling the relationships between natural zones and anthropogenic factors [2], [9].

Qualitative data were collected through non-participant observation and an online survey with open-ended questions [10], [14], [18]. Observation protocols were based on assessing students' ability to work independently with data, conduct analytical analysis, and demonstrate research activity. Open-ended survey responses were processed using content analysis. Quantitative data were compiled from the scores of two milestone assessments and the results of a student questionnaire with closed-ended questions. The closed-ended student questionnaire consisted of 10 statements and was rated using a five-point Likert scale. The internal reliability of the instrument was assessed using Cronbach's alpha coefficient. The obtained value was $\alpha=0.78$, which exceeds the threshold accepted in educational research ($\alpha \geq 0.70$) and indicates a sufficient level of internal consistency and measurement reliability.

In the statistical analysis, the quantitative data obtained in the study were processed using IBM SPSS Statistics software [1], [5], [12]. First, descriptive statistics were applied to describe the overall structure of the data, including mean values (M) and percentage distributions for academic performance indicators and survey responses. This approach made it possible to identify general trends in students' academic achievements and perceptions. To evaluate the impact of the STEM-based instructional intervention on academic outcomes, a paired-samples t-test was used. This test was designed to compare the results of the same group of participants at two time points (before and after the implementation of STEM elements). The use of the paired-samples t-test fully corresponds to a one-group pre–post research design. During the analysis, assumptions were taken into account, including the quantitative nature of the measured variables, the collection of measurements from the same participants, and visual inspection of data normality (histograms), taking into account the small sample size. The quantitative statistical results obtained were complemented by qualitative data. This approach made it possible to enhance the validity of the research findings.

Triangulation of qualitative and quantitative data strengthened the overall methodological rigor, ensuring consistency between observed student behaviors, self-reported perceptions and measurable academic outcomes. Such triangulation is widely recommended in educational research for validating claims about learning improvement in technology-enhanced environments [8], [11], [19]. Through this methodological structure, the study systematically assessed how the integration of digital geospatial tools and STEM-based instructional elements contributes to the improvement of university students' research skills within the regional geography curriculum.

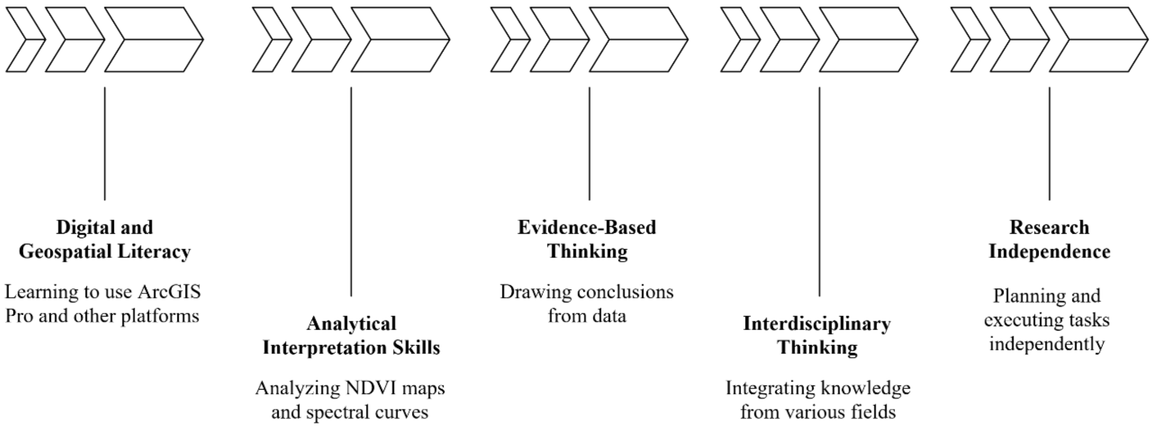

Figure 1. STEM skills development sequence

4. RESULTS AND DISCUSSION

4.1. Students' perception of STEM-based instruction introduced into the course

The results of the study showed that STEM-oriented tasks were positively perceived by students. Observations and survey data indicated that most students demonstrated increased interest and active engagement when working with real geospatial data. This trend is explained by the increase in cognitive involvement in a STEM learning environment, which has also been highlighted in previous studies [8], [7].

At the beginning of the instructional cycle, students mostly relied on procedural actions when analyzing NDVI layers, spectral reflectance curves, or climatic data. However, systematic work with the ArcGIS Pro, EOSDA Crop Monitoring, and EO Browser platforms gradually developed their competency in independently conducting analysis. This corresponds with previous findings indicating the potential of STEM tasks to foster cognitive autonomy [3], [5]. The survey results as in Table 1 shows that 92.86% of students reported improved understanding of ecological processes, and 57.14% indicated increased motivation.

Table 1. Student feedback on STEM-based tasks (n=24)

Indicator	Percentage (%)
Improved understanding of environmental data	92.86
Enhanced analytical/quantitative reasoning	42.86
Increased motivation and engagement	57.14
Found satellite interpretation difficult	28.57
Overall positive learning experience	89.29

Nevertheless, 89.29% reported a positive overall learning experience, suggesting that the instructional design effectively balanced cognitive load with achievable inquiry tasks. As noted in international studies, the findings confirmed that working with real satellite data enhances students' cognitive interest [15], [20]. Although 28.57% of students reported experiencing difficulties with spectral interpretation, this is known to be a typical phenomenon at the initial stage of learning remote sensing [21], [22]. Overall, the integration of

STEM elements into the geography course was found to increase students' motivation, learning engagement, and depth of content understanding. These findings support international research on the role of STEM in fostering interdisciplinary thinking [11], [12].

4.2. The impact of working with satellite and geospatial data on the improvement of students' analytical and research skills

4.2.1. Development of analytical thinking skills

In the process of analyzing NDVI maps, students gradually mastered the identification of fluctuations in vegetation productivity, bare soil areas, and spatial variations in moisture, as seen in Figure 2. This improvement reflects the consistent development of analytical accuracy during the instructional cycle. The observed progress corresponds to the STEM skills development sequence presented in Figure 1, which conceptually explains the transition from basic work with geospatial data toward analytical interpretation and evidence-based reasoning. Thus, Figure 1 provides the methodological framework that underpins the empirical results demonstrated in Figures 2 and 3. The dynamics of analytical skill formation identified in this study are consistent with established patterns of remote sensing skill acquisition [20], [22].

During the analysis of spectral reflectance curves, as in Figure 3, the students were able to clearly demonstrate that healthy vegetation exhibits high reflectance in the near-infrared spectral range, whereas vegetation under stress shows reduced reflectance levels. This demonstrates the emergence of skills in scientific reasoning and evidence-based explanation. Such results corroborate the findings of previous studies [8], [10] regarding the effectiveness of STEM education in developing analytical thinking.

Figure 2. NDVI maps and seasonal vegetation dynamics

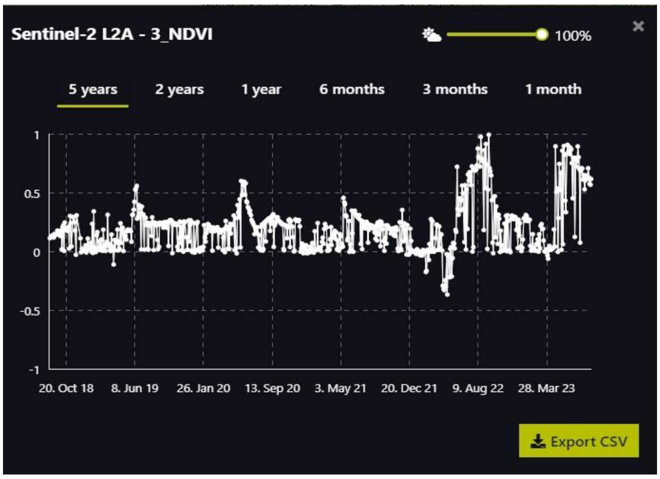

Figure 3. NDVI changes in Aktobe Oblast (2018–2023)

4.2.2. Development of interdisciplinary competencies

Calculating climatic indicators (temperature, precipitation, evaporation, humidity coefficients) and linking them to natural zones showed an increase in students' ability to think mathematically and ecologically. This corresponds with the arguments of Gao *et al.* [9] regarding the capacity of STEM to foster the solving of interdisciplinary problems.

4.2.3. Quantitative results

Table 2 shows the results of the two midterm assessments showed that students' academic performance increased from 78.4 to 80.0 points (+1.6%). Considering that the tasks in the second assessment were more complex, this increase provides evidence of the effectiveness of the STEM approach, as shown in Figure 4. Such gradual improvement is consistent with the conclusions of other studies on GIS-based short-term interventions [23]. As shown in Figure 4, with the exception of one student, the results of all participants remained stable or demonstrated steady improvement. This provides evidence that the systematic use of geospatial tools strengthens analytical skills.

Table 2. Academic performance before and after STEM-based tasks

Assessment	Mean score	Change
Midterm 1	78.4	–
Midterm 2	80.0	+1.6%

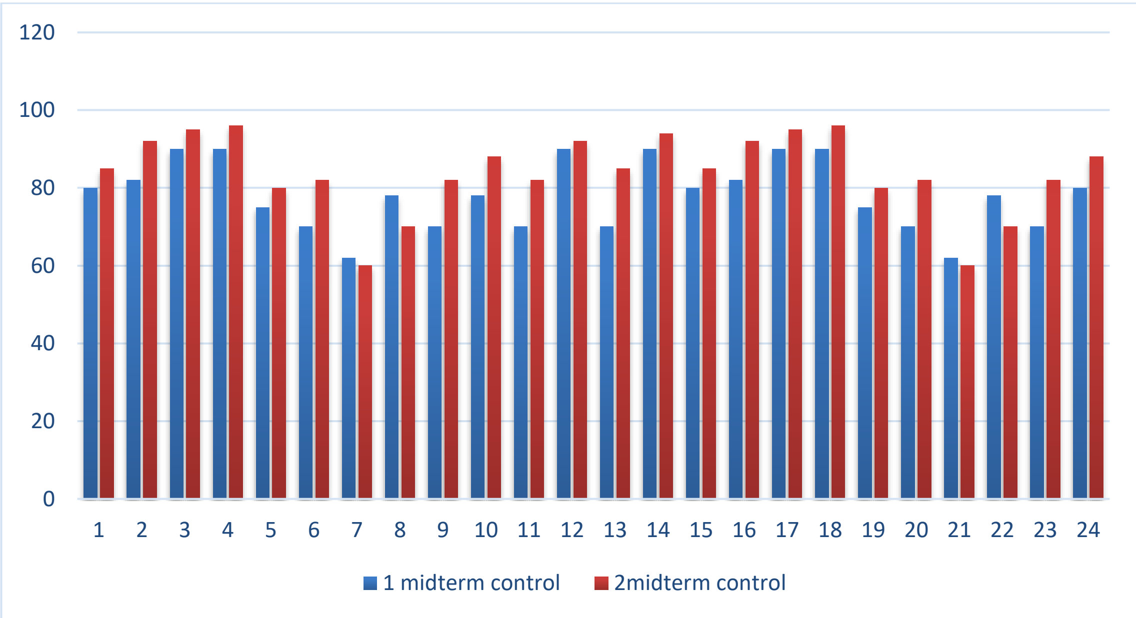

Figure 4. Progress of midterm performance in "Geography of Aktobe Oblast"

4.2.4. Broader research competencies

Figure 5 presents the frequency distribution of students' responses regarding the development of broader research competencies following the STEM-based intervention. Based on the subsequent quantitative interpretation of these frequencies, all participants (100%) reported improvement in creative skills, while 42.86% indicated enhanced mathematical thinking, 28.57% reported progress in public speaking, and 22.57% noted growth in critical thinking abilities. This combined representation allows the results to be interpreted both in terms of response distribution and relative prevalence within the study sample.

Midterm performance trends, as in Figure 4, further illustrate cumulative learning effects. Except for one student who missed practical sessions for health reasons, all participants demonstrated stable or improved performance. This trend confirms that repeated interaction with geospatial tools enhances analytical capabilities and supports sustained academic progress. These findings indicate that the STEM approach develops transversal skills, as discussed in the previous works [18], [24], [25].

4.2.5. Overall synthesis

When the two research questions are considered together, the results show that STEM-based instruction was not merely a technological enhancement but also a methodological tool that transformed students' cognitive approach to analyzing environmental data. The alignment of survey results, academic performance indicators, and in-class observations provides evidence that the STEM approach strengthens the following student competencies: i) digital and geospatial literacy; ii) skills in analytical interpretation; iii) interdisciplinary thinking; and iv) readiness for research. This is fully consistent with the international literature that describes STEM as an effective pedagogical model for reinforcing inquiry-based learning in geographic education [6], [26].

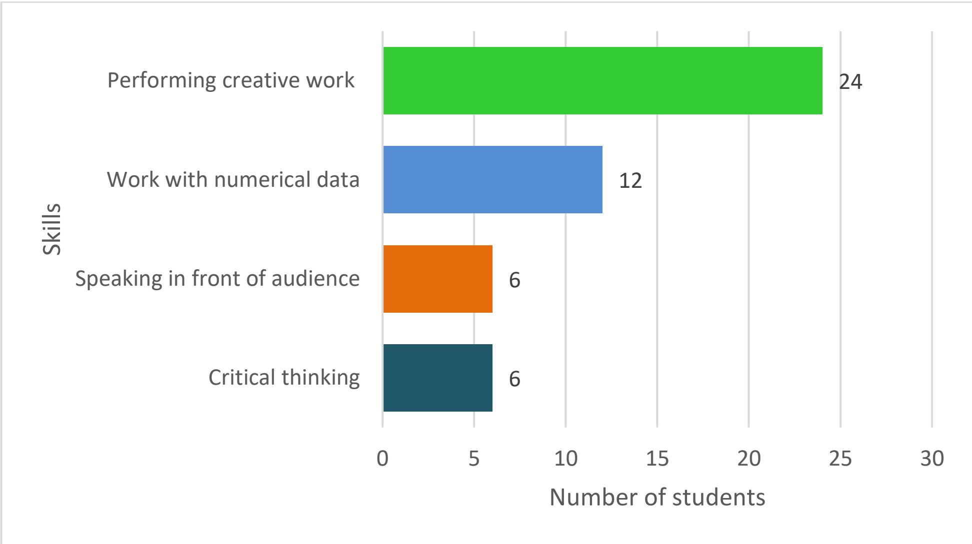

Figure 5. Skills gained through STEM-based tasks

5. CONCLUSION

The findings of this study provide empirical evidence that the integration of STEM-based components into university-level geography education creates favorable conditions for the development of students' analytical, research, and digital competencies. The use of satellite-derived vegetation indices, geospatial datasets, and climate-based calculations enabled students to apply theoretical geographic knowledge in practice and to interpret environmental processes through data-driven inquiry. Similar conclusions regarding the effectiveness of STEM-oriented instruction in strengthening analytical reasoning and research readiness have been reported in international studies emphasizing inquiry-based and technology-enhanced learning environments.

At the same time, several methodological limitations should be acknowledged, including the limited sample size and the short duration of the intervention, which restrict the generalizability of the results and preclude the assessment of long-term learning effects. Previous research highlights the importance of longitudinal and comparative designs for evaluating the sustainability of competencies developed through STEM-based instruction. Despite these constraints, the present study demonstrates the pedagogical value of integrating STEM approaches into geography education and provides a methodological basis for their further application within higher education curricula.

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AUTHOR CONTRIBUTIONS STATEMENT

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Laiskhanov Shakhislam Uzakbaevich	✓	✓				✓		✓	✓		✓	✓		
Seminar Yerkegul			✓	✓	✓	✓	✓	✓	✓	✓			✓	✓

C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
M : **M**ethodology	R : **R**esources	Su : **Su**pervision
So : **So**ftware	D : **D**ata Curation	P : **P**roject administration
Va : **Va**lidation	O : Writing - **O**riginal Draft	Fu : **Fu**nding acquisition
Fo : **Fo**rmal analysis	E : Writing - Review & **E**diting	

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [SY], upon reasonable request.

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