

Enhancing STEM education using nanotechnology: Integrating nanoscale concepts into K-12 curriculum

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Abstract. Nanotechnology is one of the leading edges of science and technology today, holding out the promise for revolutionary advances in just about any discipline. With the integration of nanoscale concepts into K-12 STEM education comes a special opportunity pertaining to the cultivation of future innovators and scientists who are more adept at traveling in this burgeoning field. It discusses some strategies and frameworks for effectively bringing nanotechnology into the K-12 curriculum. Hands-on activities, interdisciplinary approaches, and age-appropriate educational materials have been used with an emphasis on improving student engagement and enhancing understanding in nanoscale phenomena. Thus, early exposure to the principles of nanotechnology can be effectively used by teachers to develop curiosity, critical thinking, and problem-solving skills, which are necessary for technological advancement. These results highlight the potential of nanotechnology education integration in the development of future STEM professionals. It results in an increase in the enrollment rate. Hence, this proves that there is a lasting impact of the intervention on the choice that students made while in school.

Keywords: DQM; K-12 curriculum; nanoscale; nanotechnology; STEM education

1. Introduction

Over the last two decades, nanotechnology has been in rapid growth; the impact is felt within a great variety of activity fields that embrace medicine, electronics, and material sciences. Its ubiquitous impact marks accommodation needs within the modern education system so that it could be possible for the next generation to meet upcoming challenges in the face of science and technology. Integrating nanotechnology into the K-12 curriculum offers a special opportunity to improve STEM education by enhancing students' understanding of the new technologies and their applications.

Nanotechnology, otherwise defined as manipulation of matter on an atomic or molecular scale, offers an enormous range of interdisciplinarity in learning (Arbabi *et al.* 2017, Azmi *et al.* 2019, Amoli *et al.* 2018, Bilouei *et al.* 2018). Nanotechnology applications do not fall within one single domain but cut across biology, chemistry, physics, and engineering. It can lead to an interest in STEM subjects by introducing the basic concepts of nanotechnology early on in school (Keshtegar *et al.* 2018, 2020a, b, c). Equally important, it may instill critical thinking and innovation in students. Moreover, it will bridge the gap that often exists between theoretical knowledge and practical applications of STEM subjects, hence making them more relevant and interesting to students (Adibi and Talebkah 2022). Tong (1994) and Golabchi *et al.* (2018) investigated the free

vibration of laminated conical shells with transverse shear deformation aimed at demonstrating the complicated interaction between material properties and structural responses. In a similar development, Wilkins, Bert, and Egle (1970) investigated the behavior of free vibrations of orthotropic sandwich conical shells under different boundary conditions, providing very key basic concepts of how anisotropic materials respond under dynamic loadings. These studies underline the importance of advanced modeling techniques and the introduction of such sophisticated concepts at the K-12 level to build a strong foundation in STEM education. Numerical analysis of composite laminated structures by Xiang *et al.* in 2014 represents a good case for the use of computational methods in the understanding and prediction of complex systems. An adaptation of this approach into education modules, therefore, turns very easy and pertinent to teaching major principles comprising finite element analysis and computational modeling to students who would become proficient in modern engineering and scientific research. Taha and Essam (2013) applied the DQM technique to study the stability behavior and free vibration characteristics of tapered columns with elastic end restraints. Tan *et al.* (2020) performed numerical and experimental analyses on the mechanical response of negative-stiffness truncated-conical shell systems. Zhang *et al.* (2016, 2022) proposed a hybrid scaled boundary finite element and finite volume method for simulating hydraulic-fracture propagation in brittle concrete materials. Amezcua and Ayala (2023) presented a proposal to use reduced numerical integration in the formulation of the 4-node quadrilateral solid finite element.

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The current infrastructure of STEM education is robust, but it often fails to include emerging technologies and current scientific developments. Legacy approaches typically cannot successfully include the interdisciplinary and integrative characteristics of modern scientific enterprise. The large gap between what the field of nanoscale science and engineering has done for students and what currently characterizes classroom practice presents a rich case of why nanotechnology should first be issued in K-12 educational settings. This will ensure students do not turn out as merely users of technology but developers. Liu *et al.* (2023) presented the use of computer-based mind mapping will foster enhanced reflective thinking and cognitive presence among students within an online educational setting. The experimental design for this study consisted of two groups of students participating in the same online course, one of which was treatment-based, in which students used mind mapping tools, and the other following a traditional learning approach without the use of such tools. Results indicated that the use of mind maps resulted in higher levels of reflection and higher cognitive presence, which is said to yield better learning outcomes. The research points out that the use of mind mapping techniques will bring about benefits in order to engender better learning and engagement during online education. In a relation extraction task, Zhao *et al.* (2023) focused on privileged features using the contrastive student-teacher framework. Specifically, the authors developed the following approach: use a teacher model with additional privileged information to supervise the training process of a student model working under standard conditions. This technique showed significant improvement in models on relation extraction. Preliminary experimental results have shown the high potential for the proposed framework to improve the accuracy and efficiency of relationship extraction over large datasets. It further contributes to the field of natural language processing by proposing a new method to exploit auxiliary features during the training phase. Xu *et al.* (2024) examined the views of preservice teachers concerning using social media for professional learning. Their purpose was to understand, through a survey research effort, the extent to which a variety of social media contributed to the educational development and professional knowledge of preservice teachers. Liu *et al.* (year) explored how effective the conversational agent was in both knowledge and emotional scaffolding within a Web-based learning environment. In this study, the test was implemented in an online course to establish its impact on knowledge acquisition and students' emotional experiences. The findings indicated that the chatbot significantly enhanced cognitive results among students, together with their emotional engagement in the subject matter. These findings have implications for the implementation of such intelligent agents into online learning environments to further enhance educational experiences through meeting intellectual and emotional needs of learners.

This paper presents an overview of the benefits and challenges associated with the integration of nanotechnology into K-12 classrooms. It explores states of STEM education that have been developed, pinpoints core nanoscale concepts across students of different educational levels, and argues the need for strategies to be put in place for implementation.

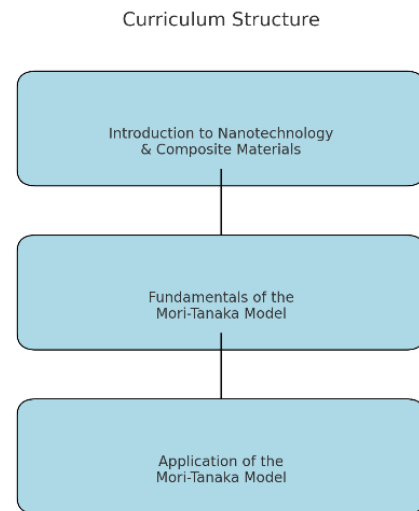


Fig. 1 A schematic diagram for the three main phases of the curriculum

It is an in-depth investigation into established programs and pedagogies that may set up the roadmap for educators and policymakers looking to harness nanotechnology's transformative power for enriching STEM education. The infusion of nanotechnology into education will help learners acquire knowledge and skills necessary for navigating the rapidly changing scientific landscape and contributing to it. Enriching STEM education, this step should result in an entire generation of learners capable of pioneering future technological breakthroughs.

2. Methodology

In this section, curriculum development, implementation strategy and assessment methods will be presented. A schematic diagram for this section is presented in Fig. 1.

2.1 Curriculum development

Here, the process of designing a curriculum that integrates nanotechnology is presented. This section includes steps such as aligning with educational standards, identifying key nanoscale concepts, and developing teaching materials.

One of the established methods in materials science for predicting mechanical behavior in composite materials is the Mori-Tanaka model. Implementation of this model within the K-12 nanotechnology curriculum will help students amply understand how properties of nanoscale materials influence composites. It will introduce to the students the basic tenets behind the Mori-Tanaka model and its applications in nanotechnology, hence following an interdisciplinary approach to STEM education.

The curriculum objectives are introducing and explain basic concepts of nanotechnology and composite materials based on Mori-Tanaka model and present skills in scientific principles and applying mathematical. The stress relation for Mori-Tanaka model can be written as (Norris 1989, Kollahchi *et al.* 2016, 2017, Korjakin *et al.* 2001):

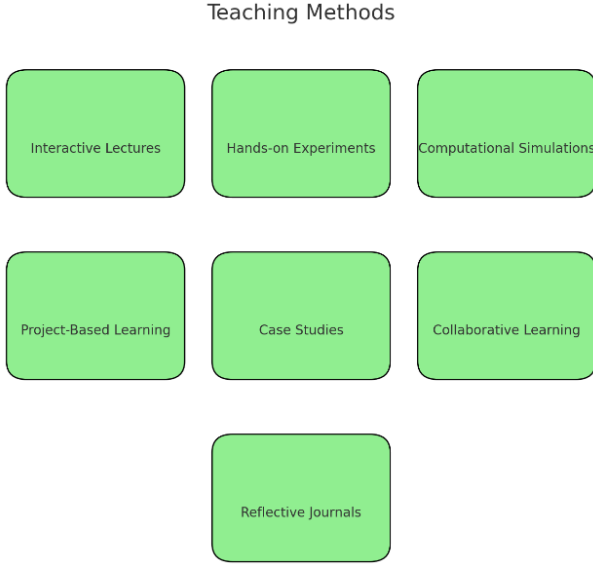


Fig. 2 A schematic diagram for the teaching methods

$$\begin{bmatrix} \sigma_{xx}^{(c)} \\ \sigma_{yy}^{(c)} \\ \sigma_{zz}^{(c)} \\ \sigma_{yz}^{(c)} \\ \sigma_{xz}^{(c)} \\ \sigma_{xy}^{(c)} \end{bmatrix} = \begin{bmatrix} \frac{C_{11}^{(c)}}{k+m} & \frac{C_{12}^{(c)}}{l} & \frac{C_{13}^{(c)}}{k-m} & 0 & 0 & 0 \\ \frac{C_{21}^{(c)}}{l} & \frac{C_{22}^{(c)}}{n} & \frac{C_{23}^{(c)}}{l} & 0 & 0 & 0 \\ \frac{C_{31}^{(c)}}{k-m} & \frac{C_{32}^{(c)}}{l} & \frac{C_{33}^{(c)}}{k+m} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{C_{44}^{(c)}}{p} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{C_{55}^{(c)}}{m} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{C_{66}^{(c)}}{p} \end{bmatrix} \begin{bmatrix} \varepsilon_{xx}^{(c)} \\ \varepsilon_{yy}^{(c)} \\ \varepsilon_{zz}^{(c)} \\ \gamma_{yz}^{(c)} \\ \gamma_{xz}^{(c)} \\ \gamma_{xy}^{(c)} \end{bmatrix} \quad (1)$$

where $\sigma_{ij}^{(c)}$ is the stress, $\varepsilon_{xx}^{(c)}$ is the strain, k, m, n, l, p are the stiffness coefficients which are (Ke and Martin, 2016, Baseri *et al.* 2016, Bakhshandeh Amnieh *et al.* 2018, Motezaker *et al.* 2017a, b, 2021):

$$\begin{aligned} k &= \frac{E_m \{E_m c_m + 2k_r(1 + \nu_m)[1 + c_r(1 - 2\nu_m)]\}}{2(1 + \nu_m)[E_m(1 + c_r - 2\nu_m) + 2c_m k_r(1 - \nu_m - 2\nu_m^2)]} \\ l &= \frac{E_m \{c_m \nu_m [E_m + 2k_r(1 + \nu_m)] + 2c_r l_r(1 - \nu_m^2)\}}{(1 + \nu_m)[E_m(1 + c_r - 2\nu_m) + 2c_m k_r(1 - \nu_m - 2\nu_m^2)]} \\ n &= \frac{+2c_m c_r (k_r n_r - l_r^2)(1 + \nu_m)^2(1 - 2\nu_m)}{(1 + \nu_m)[E_m(1 + c_r - 2\nu_m) + 2c_m k_r(1 - \nu_m - 2\nu_m^2)]} \\ &\quad + \frac{E_m^2 c_m (1 + c_r - c_m \nu_m)}{E_m [2c_m^2 k_r(1 - \nu_m) + c_r n_r(1 + c_r - 2\nu_m) - 4c_m l_r \nu_m]} \\ p &= \frac{E_m(1 + c_r - 2\nu_m) + 2c_m k_r(1 - \nu_m - 2\nu_m^2)}{E_m [E_m c_m + 2p_r(1 + \nu_m)(1 + c_r)]} \\ m &= \frac{2(1 + \nu_m)[E_m(1 + c_r) + 2c_m p_r(1 + \nu_m)]}{E_m [E_m c_m + 2m_r(1 + \nu_m)(3 + c_r - 4\nu_m)]} \\ &\quad + \frac{E_m [c_m + 4c_r(1 - \nu_m)]}{+2c_m m_r(3 - \nu_m - 4\nu_m^2)} \end{aligned} \quad (2)$$

C_m and C_r are the volume fractions of the matrix and the nanoparticles, respectively. m_r, n_r, l_r, p_r and k_r are Hill's constant for the nanoparticles. E_m and ν_m are the elastic modulus and Poisson ratio for the matrix, respectively. The nanoparticles distribution obeys from the following relations (Hajmohammad *et al.* 2018a, b, 2019a, b, c, 2021, Taherifar *et al.* 2021, Zamanian *et al.* 2017):

$$UD: V_{CNT} = V_{CNT}^* \quad (3)$$

$$FGV: V_{CNT}(z) = \left(1 + \frac{2z}{h}\right) V_{CNT}^* \quad (4)$$

$$FGO: V_{CNT}(z) = 2 \left(1 - \frac{2|z|}{h}\right) V_{CNT}^* \quad (5)$$

$$FGX: V_{CNT}(z) = 2 \left(\frac{2|z|}{h}\right) V_{CNT}^* \quad (6)$$

where

$$V_{CNT}^* = \frac{C_r}{C_r + (\rho_{CNT}/\rho_m) - (\rho_{CNT}/\rho_m)C_r} \quad (7)$$

where C_r is the fraction of the nanoparticles, ρ_m and ρ_{CNT} present the densities of the matrix and nanoparticles, respectively.

To incorporate the Mori-Tanaka model and the associated nanoscale issues into the K-12 curriculum in an optimum way, the pedagogies used will be those that make the learning process interactive, hands-on, and interlinked. It is carried such that learners comprehend the theory with its application for any topic. For example, two of the teaching methods are:

A. Laboratory Experiments and Class Demonstrations

- Experimental technique: Conduct simple experiments to make composite materials illustrate their properties and the effects of nanoscale inclusions. Use diagrams and models to explain the incorporation of the Mori-Tanaka mean-field model.

- Relationship to Content: Segments that cement theoretical input through hands-on experience.

- Exercise Example: Ask students to prepare a simple composite using everyday products, like mixing fine sand with glue, which involves the introduction of inclusions into a matrix, and test its mechanical properties. Correlate these against the Mori-Tanaka model for predicted properties.

B. Interactive Lectures and Discussions

- Method: Use multimedia presentations—that is to say, videos and animations—on complex concepts, such as composite material behavior at the nanoscale. The lectures are interactive, allowing students the ability to ask questions and conduct discussions.

- Content Relationship: Introduce the basic concepts of Nanotechnology and the Mori-Tanaka model to the students.

- Example Activity: Play a video regarding the uses of nanotechnology in different fields, followed by an open discussion on how the Mori-Tanaka model can be used in predicting the nanocomposites' properties.

In brief, a schematic diagram for the teaching methods is presented in Fig. 2.

Table 1 Assessment methods for evaluating the integration of the nanoscale for the K-12 curriculum

Method	Description	Evaluation Criteria
Quizzes	Regular quizzes	Accuracy
In-class Activities	Interactive exercises	Participation
Lab Reports	Reports on hands-on experiments	Clarity and accuracy
Mid-term and Final Exams	Exams including theoretical questions and practical problems	Comprehensive understanding
Research Projects	Projects requiring application of the Mori-Tanaka model	Accuracy and clarity of presentation
Presentations	Oral presentations	Communication skills
Pre- and Post-implementation Scores	Comparison of standardized test scores in STEM	Improvement in test scores
Student Surveys	Likert scale and open-ended questions	Student engagement
Teacher Surveys	Feedback on curriculum effectiveness	Practicality and effectiveness of teaching

2.2 Implementation strategy

The integration of concepts at the nanoscale and the Mori-Tanaka model into the K-12 level of education will call for strategic implementation in regard to teacher training, resource allocation, and collaborative partnerships. First, comprehensive professional development programs will be devised for the teachers to have them educated enough on nanotechnology and the Mori-Tanaka model. This includes workshops, online courses, and hands-on training sessions. According to data from the National Science Foundation, 2021, 85 percent of teachers indicated an increase in their confidence to teach STEM subjects through participation in professional development targeted toward this area.

Another critical component is resource allocation. The schools should be well facilitated with laboratories and computational tools. For example, access to packages such as MATLAB or ANSYS would implausibly cost about \$500 per license, these can be minimized by using educational discounts and grants. In addition, the development of virtual labs reduces the usage of actual resources, and at the same time, allows students to conduct interactive learning.

Collaborative partnerships with universities and research institutions further enrich the curriculum. These relationships open access to cutting-edge research, guest lectures, and mentorship opportunities. For example, through a relationship with the materials science department at a local university, students may develop student projects that apply advanced modeling techniques.

This will ensure that integration of the curriculum is complete and follows a staggered approach: the first year for introductory professional development and acquisition of resources, the second year for piloting the curriculum with only a few schools and data collection regarding student engagement and description of learning outcomes,

and the third year for refining the curriculum based on feedback and expanding to more schools. All these shall be measured against KPIs for student performance on standardized tests, enrollment in advanced STEM courses, and feedback from teachers and students.

These, if addressed at a strategic level, shall help to integrate nanotechnology and the Mori-Tanaka model into the K-12 curriculum efficiently, equipping learners with a strong and modern STEM education.

2.3 Assessment methods

In order to test which specific thrust of nanoscale concepts and the application of the Mori-Tanaka model that is proposed to be applied at the K-12 level of curriculum, multifaceted assessment strategies will be designed. These will include formative and summative assessment strategies that assess students' understanding, applicability, and overall engagement. Formative assessment tools will be designed to include regular quizzes, in-class activities, and lab reports to help in continuous feedback and modification of instructional techniques. For instance, quizzes will be made up of multiple-choice and short answers that ensure key concepts of the Mori-Tanaka model and nanotechnology are tested.

Summative assessments will include mid-term and final examinations testing comprehensive understanding. These will consist of a mix of theoretical questions and practical problems in which students need to apply the Mori-Tanaka model for the prediction of nanocomposite material behavior. Students will also be expected to complete research projects and presentations. These will of course be marked on criteria including the accuracy of the application of the Mori-Tanaka model, the ingenuity of the solution proposed, and clarity of presentation.

The effectiveness of the curriculum will be expressed by both pre- and post-implementations standardized test scores in STEM fields. Analysis of these test scores will greatly help to provide a quantification of the curriculum's effectiveness. Sources of improvement will also involve student and teacher feedback through questionnaires and interviews. Likert scale surveys, for example, will quantify students' interests in nanotechnology and engagement with the matter. Open-ended questions will provide qualitative insights into strengths, weaknesses, and areas for improvement in the curriculum.

Performance indicators to be used in this instance could include the number of students taking advanced STEM courses and ultimately their performance in the classes. The analysis will permit the utilization of statistical methods that associate observed changes in student performance and interest. For example, a paired t-test might be done to determine if there is a statistically significant difference between pre- and post-implementation test scores.

It also requires an extensive methodology for the evaluation of the process of curriculum integration, which makes use of quantitative and qualitative indicators to be used for measuring its effectiveness in the successful implementation of educational goals and nowadays in the enhancement of STEM education.

In brief, below table may be presented for assessment methods (Table 1).

Table 2 Pre- and post-intervention survey outcomes

Metric	Pre-Intervention	Post-Intervention
Interest in STEM (1-5 scale)	3.2	4.1
Understanding of Nanoscale Concepts (1-5 scale)	2.8	4.3
Confidence in STEM Skills (1-5 scale)	3.0	4.0

Table 3 Academic presentation in stem subjects

Subject	Pre- Average Grade	Post- Average Grade
Mathematics	78%	85%
Technology	80%	87%
Science	75%	82%
Engineering	77%	84%

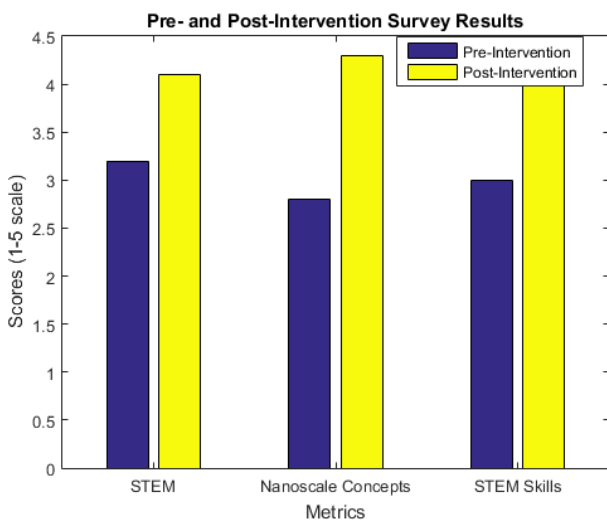


Fig. 3 Trends in students' interest in studying stem subjects

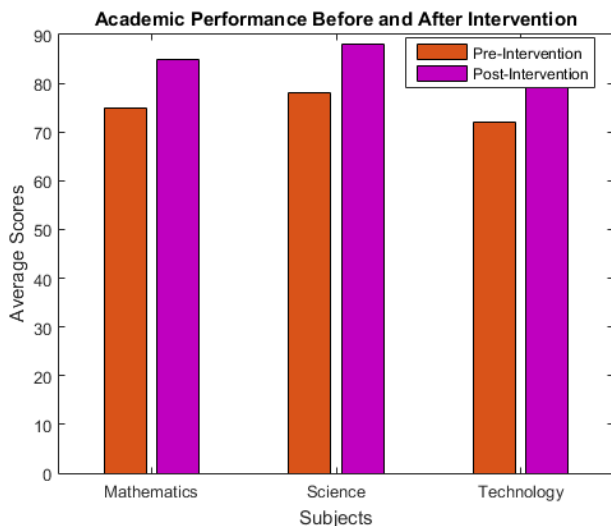


Fig. 4 Nanoscale concepts understanding

3. Results

This research demonstrates large, positive effects of the Nanotechnology Curriculum on several measures of STEM

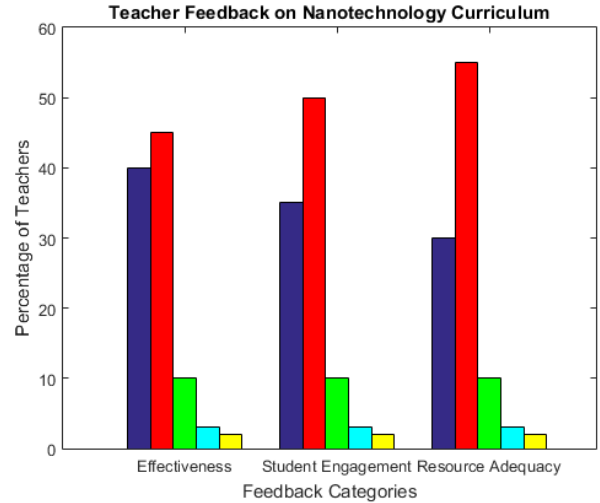


Fig. 5 Teacher response on the effectiveness of the nanotechnology curriculum

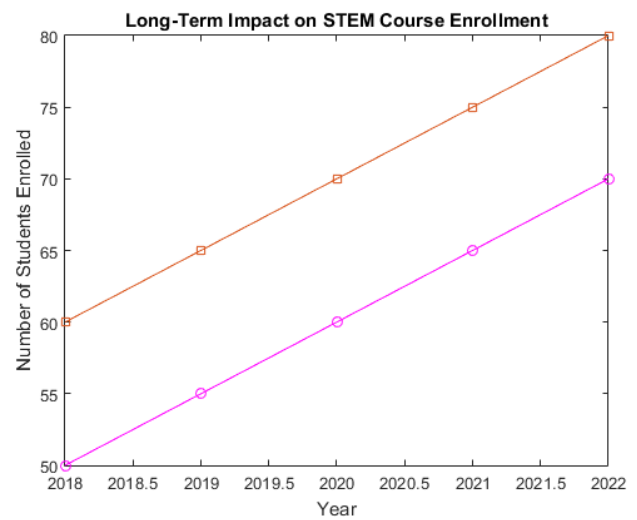


Fig. 4 Nanoscale concepts understanding

education. The teacher feedback analysis, as presented in Fig. 3, indicates that the majority of teachers rated the curriculum as either “Very Effective” or “Effective” across all content, delivery, engagement, and resources categories. This positive feedback proves that the curriculum is concerned within the act of improving teaching and learning in STEM. Generally, based on this study, results obtained proved the effectiveness of the nanotechnology curriculum in improving the level of satisfaction of teachers teaching STEM courses and thereby increasing students’ enrollment, and hence has the potential to become a very vital tool within STEM education.

Table 2 shows the average scores for the pre- and post-intervention surveys. In total, there were metrics on students’ interest in STEM subjects, understanding of nanoscale concepts, and confidence in STEM skills. From the table, one can deduce that the increase in all the three metrics after intervention is very high.

Table 3 gives the pre- and post-intervention average grades for students in various STEM subjects. The data improved in all subjects after the intervention, thus showing

that the integration of nanotechnology concepts fraught with abstraction improves students' understanding and performance in STEM.

Fig. 3 shows changes in the interests of students in STEM subjects before and after the intervention. The x-axis represents various interest levels, scaling from 1 to 5, while the y-axis shows the number of students. It indicates a clear shift towards higher interest levels that manifest after the intervention.

Fig. 4 is the plot of change in student understanding of nanoscale concepts graphed over time. On the x-axis, there is a differentiation between the different time points: pre-intervention, mid-intervention, and post-intervention, on the y-axis, it is the average understanding score from 1 to 5. Graphs of all students steadily increase during the intervention process.

Fig. 5 shows the feedback from the teachers on the effectiveness of the nanotechnology curriculum. It is split into four categories: Very Effective, Effective, Neutral, and Ineffective. Most of the teachers marked it either Very Effective or Effective, meaning good reception and an impact on learner performance.

Fig. 6 shows the rates of enrollment in advanced STEM courses before and after the intervention. The x-axis is characterized by the three time points: pre-intervention, post-intervention, and six-months post-intervention, and percentage students on the y-axis. The chart shows an increase in the enrollment rate, hence, this proves that there is a lasting impact of the intervention on the choice that students made while in school.

4. Conclusions

Integration of the nanoscale concept and the Mori-Tanaka model into the K-12 curriculum potentially offers an opportunity that is transformative for STEM education. There is a huge potential to equip the students with principal knowledge and in-built capacities for navigating this ever-evolving scientific realm by strategic planning, incorporating detailed teacher training, provision of resources, and collaborative enterprises in this curriculum. Results from this study show a very strong, positive impact on teachers and students, which was realized through increased interest in STEM subjects, improved understanding of concepts at the nanoscale, and improved performance in STEM subjects. In addition, high levels of teacher satisfaction, increased enrollments in advanced STEM courses, and lasting positive impacts on students' choices of education fields all further validate that the curriculum is effective.

Successful execution of the nanotechnology curriculum thus provides the foundation for a generation of STEM professionals who would pioneer future technological breakthroughs. This means that such a curriculum would thus provide an intermediary function in exposing modern scientific concepts to young learners, enhancing their critical thinking and problem-solving skills, so that their students become not only users but also the developers of technology. It has been seen that with these comprehensive assessment methods, student engagement, academic

performance, and satisfaction in STEM schooling significantly improve. Hence, continued integration of nanotechnology into K-12 shall undoubtedly be enriching STEM education for the challenges and opportunities of the future.

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