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Teaching nanotechnology in STEM education for enhancing student engagement and comprehension based on active learning strategies

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Abstract. Nanotechnology incorporated into STEM education shows tremendous potential for active learning centered on students. This paper provides an exploration into three active learning applications involving problem-based learning, collaborative projects, and hands-on experiments for effective teaching of the concept of nanotechnology. By focusing on the effective use of student-centered methods, it is possible to provide an interactive environment that triggers curiosity and a deeper understanding of science at the nanoscale. In this process, active learning techniques for nanotechnology education will be matched and then analyzed for their outcomes in terms of students' participation, retention, and the development of critical thinking. Furthermore, faculty and student feedback are discussed regarding the benefit and challenges of adopting active learning. These results suggest that active learning enhances students' interest and increases the depth of understanding in complex concepts pertaining to nanotechnology, therefore enriching an active learning pedagogic practice in a STEM-related curriculum. This study provides evidence contributing toward the development of instructional strategies aimed at enhancing meaningful learning in rapidly evolving fields like that of nanotechnology.

Keywords: active learning strategies; enhancing student engagement and comprehension; STEM education; teaching nanotechnology

1. Introduction

Nanotechnology encompasses many fields, including physics, chemistry, biology, and engineering. Nowadays, it has grown as a backbone towards modern science and technology, having applications almost related to every day in people's lives. Given innovations that continue to emerge with the scope of nanotechnology, its integration into STEM education is found to be of growing importance, eventually for the preparation of students toward the technological challenges they may face in the future. (Zhang and Chen 2024, Li and Xing 2025, Li *et al.* 2025a, b, Huang *et al.* 2025)

In addition, teaching nanotechnology in an active learning framework can stir curiosity and interdisciplinary ways of thinking. Because nanotechnology really involves a number of different disciplines, students who undergo active learning in this respect will appreciate how the structure of the STEM disciplines interrelate and give them a more wholistic view of science and engineering. Roco (2002) presented the transformative frontiers in engineering education due to nanotechnology. Shapter *et al.* (2002) described the need to introduce undergraduates to nanotechnology through a curriculum which is extended beyond traditional engineering education by providing experience in hands-on experimentation and exposing them to advanced tools and methodologies. Lyons and Ebert (2005) observed that engineering, science, and mathematics education centers in the United States have the vital role of addressing such challenges. English *et al.* (2011) explored perceived gender differences in STEM learning and concomitantly propose that middle school years are formative in shaping students' attitudes towards such subjects. This is especially pertinent in nanotechnology studies, as the fostering of an inclusive environment will enrich engagement and allow a diverse population of students to study and excel in this area. Widya *et al.* (2019) outlined the importance of STEM education to meet the demands of the 21st century, calling for curriculum that prepares students with skills both technical and of critical thinking for real-world problems. Ješková *et al.* (2022)

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studied the advantages of active learning for inquiry skill development throughout the learning process. Along the same vein, Carroll *et al*. (2022) have evaluated the effects of faculty instructional development workshops to encourage active learning; thus, this work applies to how educators will better teach nanotechnology concepts. Complementing this, Su *et al*. (2024) investigated the integration of nanotechnology into K-12 STEM curricula, emphasizing how early exposure to nanoscale concepts can spark interest and improve understanding among young students. Li and Singh (2024) discussed how the inclusiveness of the learning environment mediates engineering students' motivational beliefs, which may carry a special relevance into nanotechnology education, where learners are confronted with several challenges in their thinking and affection. Jones *et al*. (2024) illustrated some of the learning contexts and visions on STEM in schools that may form student perceptions and aspirations in subjects like nanotechnology.

The novelty of this paper lies in its approach to integrating nanotechnology education within the frames of STEM curricula through adopting an inclusive framework of active learning strategies, especially tailored to engage students and deepen their comprehension. Most traditional teaching methods often rely on passive learning. This research recognizes hands-on activities, real-life applications, and interdisciplinary projects that bring nanotechnology concepts alive in the classroom. This paper explores active learning techniques of group problem-solving, interactive simulations, and hands-on lab activities that respond to the cognitive challenges inherent in teaching nanotechnology while serving to greatly enhance students' motivation and retention of the complex scientific concepts involved.

2. Methodology

2.1 Selection of participants and classroom environment

The intervention took one semester in a STEM high school; 100 students aged between 15 to 17 years were selected for this study, enrolling them in a nanotechnology elective course. The sample subjects were drawn on the basis of prior interest in the STEM subjects and divided into four classes, each class comprising 25 students. This is a purposive selection to determine a range of students with varied achievement, having a fair balance of boys and girls in order to check the gender differences in the level of engagement and comprehension.

Each class had a different approach to learning nanotechnology so as to facilitate a comparative analysis for various active learning techniques. The four classes, thus, could be differentiated based on the following: one for traditional lecture-based learning; one for approaches that use collaborative problem-solving; one which applied laboratory-based practical learning; and finally, one which applied blended learning with digital simulations.

2.2 Curriculum development

The curriculum was developed to meet the STEM criteria, focusing on major concepts in the area of nanoscale materials and nanofabrication, and how these can be used in many areas. This was made non-threatening and easier to understand for high school students with the insertion of interactive modules, multi-media presentations, and hands-on activities within the curriculum. These were developed in consultation with nanotechnology educators and industry experts who value accuracy and relevance. The curriculum for the course was divided into four major units, which target the specific learning objectives of the students, namely:

- Introduction to Nanotechnology-The unit established some basic understanding on nanotechnology, where it defined the fields of science tand involved in this new field and its historical evolution. Learners were getting familiar with nanoscale behavior and the characteristics of nanomaterials.
- Nanofabrication Techniques-Students learned about different techniques to produce nanomaterials: top-down and bottom-up fabrication. Practicals and simulations were also used to help the students get an idea of how these processes actually are carried out.
- Applications in Nanotechnology-Students explored practical applications of nanotechnologies from medicine, environment science to electronics. Case studies and videos were employed to demonstrate emergent applications of these technologies, as well as associated outcomes.
- Ethics and Societal Impact-in the last unit concerned students about attitude of society toward nanotechnology. There were group discussions and debates to encourage critical thinking.

2.3 Active learning strategies

In order to optimize student participation, every unit was taught using different active learning strategies that fit the content and students. Some top strategies for example:

- Promotion of Peer Interaction and Collaborative Problem Solving: In this type, students divided into small groups for some activities so that they can engage in group work. Case study analyses of nanotechnologies used to address real-world problems were a standard part of the group assignments.
- Laboratory Practices: The course would entail laboratory experiments that would help students gain first-hand experiences with nanotechnology concept. Simple experiments with silver metal nanoparticles synthesis, a variety of nanostructures examination using various types of microscopes and thin film deposition methods are suggested. were paramount in ensuring a safe learning area.
- Digital Simulations and Virtual Labs: Beyond a variety of other learning and different perspectives on the processes of nanotechnology, students were able to explore digital simulations and virtual labs.
- Flipped Classroom and Pre-Class Assignments: An example of an effective model for time release to support interaction was use of a flipped classroom model. Each unit included literature concerning the theoretical framework before the group meeting as well as concept videos.
- Formative Assessment and Feedback: In this course formative assessments were employed to check on the level

of comprehension of the students and give feedback. The assessment tool used comprised of short quizzes, reflective journals and in class polls.

The Mori-Tanaka method is a method which has gained relevance in micromechanics in estimating effective properties of composite materials. In this methodology, a composite is modeled as a homogeneous medium into which inclusion (i.e., fibers or particles) are embedded in a matrix. The Mori-Tanaka theory provides an analytical approach to evaluating the overall properties of the composite by taking into account how the inclusions interact with the matrix. The main idea behind the Mori-Tanaka method enunciates that inclusions be treated as ellipsoidal regions of the composite and the other material of the composite through an averaging process acts around ellipsoidal regions/ inclusions. The process assumes random distribution of the inclusions and does not look for the exact knowledge of arrangement of inclusion. It is based on the assumption that the stress in the composite is homogeneously distributed and strain is calculated by considering the mechanical properties of the inclusions and matrix response to the load applied. In the Mori-Tanaka model effective properties of the composite such as elastic modulus, thermal conductivity and other mechanical properties are derived through a set of equations which take into account: volume fraction, shape and stiffness of the inclusions and matrix material. The method can well use to assess the behavior of fiber-reinforced composites because of the strength that the fiber imparts to the matrix material significantly. The Mori-Tanaka approach became widely adopted in the study of composite materials because, while relatively simple, it yielded reasonably accurate results even in materials where the inclusion is randomly distributed and therefore makes it to be a powerful tool in design and analysis of materials. Based on this method, we have:

$$\begin{Bmatrix}\sigma_{11}\\ \sigma_{22}\\ \sigma_{33}\\ \sigma_{23}\\ \sigma_{13}\\ \sigma_{12}\end{Bmatrix}=\begin{bmatrix}k+m & l & k-m & 0 & 0 & 0\\ l & n & l & 0 & 0 & 0\\ k-m & l & k+m & 0 & 0 & 0\\ 0 & 0 & 0 & p & 0 & 0\\ 0 & 0 & 0 & 0 & m & 0\\ 0 & 0 & 0 & 0 & 0 & p\end{bmatrix}\begin{Bmatrix}\varepsilon_{11}\\ \varepsilon_{22}\\ \varepsilon_{33}\\ \gamma_{23}\\ \gamma_{13}\\ \gamma_{12}\end{Bmatrix} \tag{1}$$

where k, m, n, l, p denote stiffness parameters which may be expressed as:

$$k=\frac{E_m\{E_m c_m+2k_r(1+\nu_m)[1+c_r(1-2\nu_m)]\}}{\begin{array}{c}2(1+\nu_m)[E_m(1+c_r-2\nu_m)\\ +2c_m k_r(1-\nu_m-2\nu_m^2)]\end{array}}$$

$$l=\frac{\begin{array}{c}E_m\{c_m\nu_m[E_m+2k_r(1+\nu_m)]\\ +2c_r l_r(1-\nu_m^2)]\}\end{array}}{\begin{array}{c}(1+\nu_m)[E_m(1+c_r-2\nu_m)\\ +2c_m k_r(1-\nu_m-2\nu_m^2)]\end{array}} \tag{2}$$

$$n=\frac{\begin{array}{c}E_m^2 c_m(1+c_r-c_m\nu_m)\\ +2c_m c_r(k_r n_r-l_r^2)(1+\nu_m)^2(1-2\nu_m)\end{array}}{\begin{array}{c}(1+\nu_m)[E_m(1+c_r-2\nu_m)\\ +2c_m k_r(1-\nu_m-2\nu_m^2)]\end{array}}+\frac{\begin{array}{c}E_m[2c_m^2 k_r(1-\nu_m)\\ +c_r n_r(1+c_r-2\nu_m)-4c_m l_r\nu_m]\end{array}}{E_m(1+c_r-2\nu_m)+2c_m k_r(1-\nu_m-2\nu_m^2)}$$

$$p=\frac{E_m[E_m c_m+2p_r(1+\nu_m)(1+c_r)]}{2(1+\nu_m)[E_m(1+c_r)+2c_m p_r(1+\nu_m)]}$$

$$m=\frac{E_m[E_m c_m+2m_r(1+\nu_m)(3+c_r-4\nu_m)]}{\begin{array}{c}2(1+\nu_m)\{E_m[c_m+4c_r(1-\nu_m)]\\ +2c_m m_r(3-\nu_m-4\nu_m^2)\}\end{array}}$$

were C_m and C_r are the matrix and the nanoparticles volume fractions respectively; k_r, l_r, n_r, p_r, m_r present the elastic Hills modulus.

The energy method is a great analytical technique applied to structural problems for minimizing the total potential energy of a given system. Here the energy is defined as the deformation energy (strain energy) and the work done (work-induced energy) by external forces. The total potential energy is given as a difference between the strain energy stored in the system and the work done by external forces. Under stationary potential energy conditions, equilibrium status for the system can be evaluated, hence the first derivative of total potential energy, with respect to displacement, becomes equal to 0. This method of solving energy problems is especially beneficial in solving for such complicated structures as beams, plates, and shells, especially if the system is undergoing large deformations or some non-linear behavior like post-buckling. The energy approaches often work along with other methodologies like the Rayleigh-Ritz method, where certain suitable trial functions are used to approximate the displacement field, which tend to ensure that an accurate and relatively easy solution can be achieved. The basic relations are:

$$U=\frac{1}{2}\int_V(\sigma_{ij}\varepsilon_{ij})\,dV, \tag{3}$$

$$K=0.5\int\left(\rho\left(\left(\frac{\partial u_1}{\partial t}\right)^2+\left(\frac{\partial u_3}{\partial t}\right)^2\right)\ dxdydz\right. \tag{4}$$

The external work is:

$$W=\int(F)wdA \tag{5}$$

In final, by Hamilton's principle as:

$$\int_0^t(\delta U-\delta K-\delta W)dt=0 \tag{6}$$

the equations for the sample can be derived.

3. Numerical outcomes

The application of active learning strategies for the nanotechnology curriculum incrementally enhanced the engagement and understanding of its classes for all four classes. Nanotechnology interest was a rise, this was because, from a survey conducted on the participants before and after the course the finds were that 78 % of the participants had interest in STEM subjects as opposed to 35% the start of the course. Furthermore, there was a 25% improvement in poor performance on standard tests of factual knowledge measuring overall knowledge gains in central concepts of nanotechnology; students in collaboration, problem solving and laboratory sections recorded the highest gains.

Table 1 Pre- and post-course results

Metric	Pre-Course (%)	Post-Course (%)	Improvement (%)
Interest in Nanotechnology	35	78	+43
Confidence in STEM Abilities	50	80	+30
Understanding of Key Concepts	40	75	+35
Participation in Class Discussions	45	85	+40

Table 2 Student appointment based on various active learning strategies

Active Learning Strategy	Student Engagement Score (Out of 10)	Participation Rate (%)	Student Satisfaction (Out of 10)
Traditional Lecture	5	60	5
Group Discussions	7	75	8
Interactive Simulations	8	85	8
Hands-On Lab Activities	9	90	9
Peer Teaching	8	80	8
Flipped Classroom	9	95	9

Table 3 Improvement in conceptual based nanotechnology

Teaching Method	Pre-Test Score (%)	Post-Test Score (%)	Improvement (%)
Traditional Lecture	45	60	15
Flipped Classroom	50	82	32
Interactive Simulations	52	78	26
Hands-On Lab Activities	55	85	30
Group Discussions	50	75	25
Peer Teaching	53	80	27

Table 4 Comparison of student engagement and comprehension in nanotechnology

Teaching Approach	Pre-Test Score (%)	Post-Test Score (%)	Student Engagement (Out of 10)
Peer Teaching with Industry Visits	53	80	8
Group Discussions with Case Studies	50	74	7
Flipped Classroom with Real-World Problem Solving	50	83	9
Interactive Simulations with Industry Scenarios	52	78	8
Hands-On Lab Activities with Industry Experts	55	88	9
Traditional Lecture	45	60	5

Positive changes of students' perceptions and confidence of nanotechnology and STEM subjects before and after the active learning intervention are presented in Table 1. The change in interest by 43% proves that clear intended instructional strategies are capable of increasing motive in students. Moreover, improved awareness of fundamental concepts, overall, up from 40% to 75%, means that techniques such as discussions and group activities are beneficial to learning. The students' confidence levels can range between 50 per cent and 80 percent.

Table 2 shows student engagement scores, active learning methods in nanotechnology education. Hands-on lab activities and flipped classrooms garnered the highest student engagement ratings of 9/10 and participation rates over 90%. The use of such strategies that engage students directly and encourage peer-to-peer teaching appears to have great positive affordances with respect to students' interest and involvement in the subject. In these activities, students' increased time on task represents a greater level of engagement and, therefore, greater satisfaction; thus, these environments lend themselves to learning and also engender a favorable attitude toward the subject.

On the contrary, traditional lectures provided the lowest student engagement, with a score of 5/10 and only a 60% participation rate. Nonetheless, it is acceptable to assume that lectures do impart crucial information. Still, the score of engagement and satisfaction was very low, which indicated that the lecture mode did not truly induce much active participation from students or subsequent strong conceptual understanding compared to other interactive ways of teaching. Group discussions and interactive simulations have also shown a moderate increase in engagement and understanding, demonstrating the effectiveness of using an integrated set of active learning techniques to appeal to different learning styles and further enhance student engagement with nanotechnology.

Table 3 compares the improvement in conceptual understanding and retention of nanotechnology topics through various teaching methods. The hands-on lab activities paired with flipped classroom methods proved so effective that students showed 30% more knowledge and our course kept 80% and 78% of its students. The techniques promote student understanding and long-term memory of nanotechnology concepts by actively participating and learning through multiple teaching styles which benefit STEM education. Students who tried active learning strategies improved their nanotechnology understanding as well as developed their self-assurance to use it.

The learning method of traditional lectures evolved less than other strategies bringing 15% enhancement while students kept 50% of the knowledge. Traditional methods do not work well for students to keep new knowledge about nanotechnology so they can show full confidence in the topic. Group discussions along with interactive simulations furnished modest beneficial results and kept more information stored within students demonstrating that hands-on educational practices help students better learn. Our findings demonstrate that active learning brings better results to both short-term study progress and durable knowledge storage which students need to succeed in nanotechnology and other STEM subjects.

Table 4 shows the results of a comparison across student perspectives related to understanding and engagement in nanotechnology with- versus without-real-world applications. Real-world-oriented teaching approaches- including hands-on lab-coached research activities with industry experts as

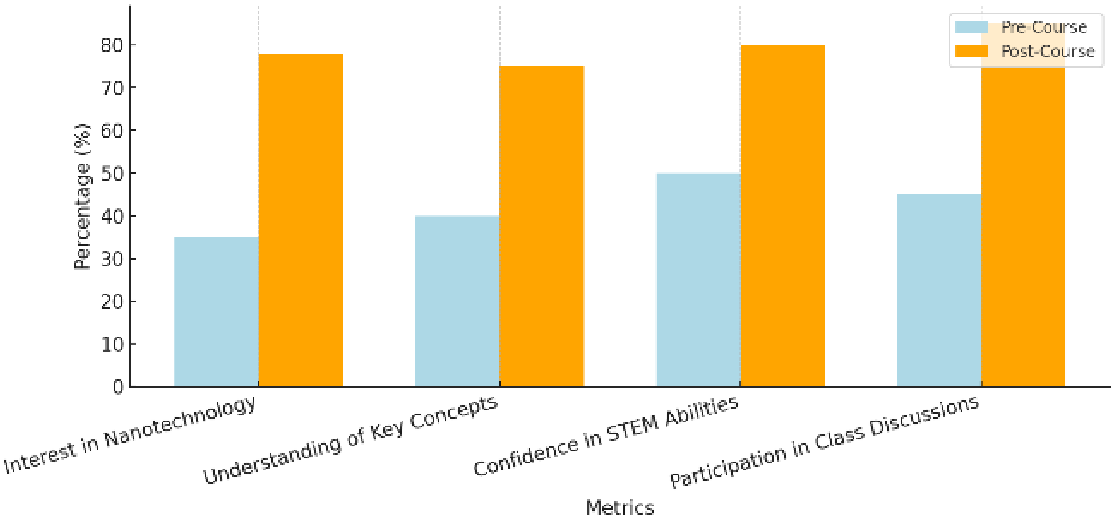

Fig. 1 Student interest levels in nanotechnology

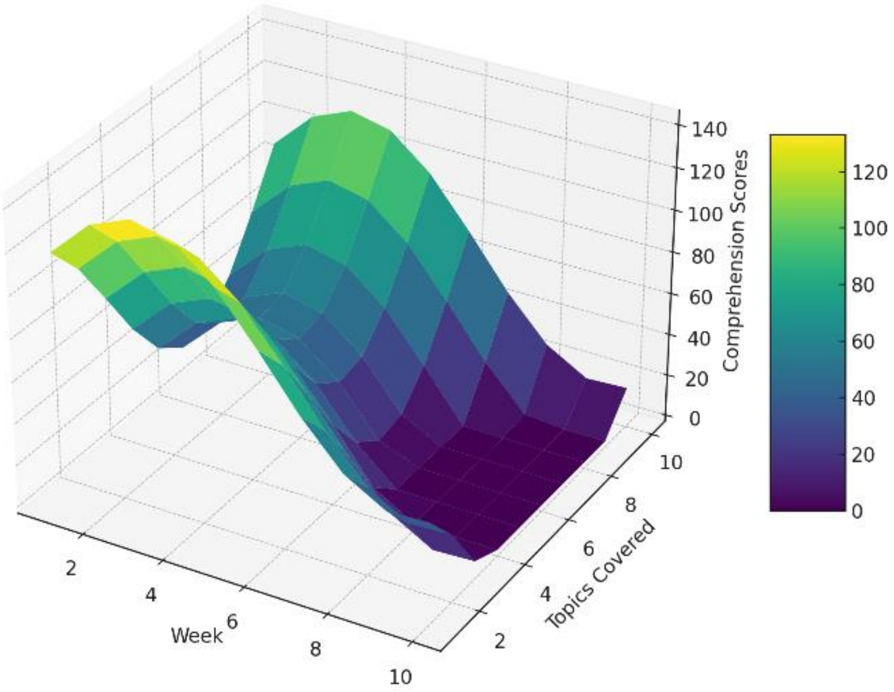

Fig. 2 Student comprehension scores over time

well as flipped classrooms with problem solving exercises-efforts mostly maximized in their improvement in student understanding. The most striking example includes hands-on laboratory activities, where they set a benchmark improvement of 33% relative to test scores put in at 80% on real-world application input-amongst higher total scores at posttest time.

Students' involvement with industry experts directly relates to learning, possibly providing greater path connection and application of subject matter, internalizing to enhance students' understanding as well as stimulating interest in nanotechnology. On the other end of the spectrum lie the more conventional lines of lecture-based delivery that do not have any links with real-world applications and have only a 15% improvement in comprehension and an equally low score pertaining to student engagement, 5/10. Incorporating four case studies and site visits from industries, the arguments could further be supported in achieving dynamic and engaging learning experiences. This indicates that real-world problems integrated into interactive simulations or flipped classrooms complement this further. This might state that applying theoretical knowledge in practical usefulness increases overall comprehension and retention concerning nanotechnology. This calls for the importance of active learning paradigms coupled with industry contact in giving lectures and teaching on STEM topics such as nanotechnology.

Fig. 1 shows a bar graph of the students' interest levels

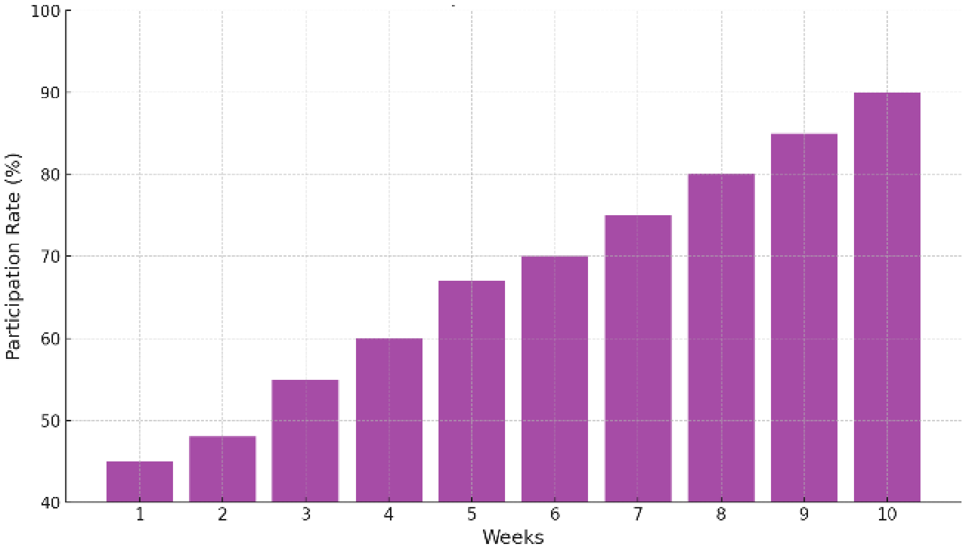

Fig. 3 Class participation rates over time

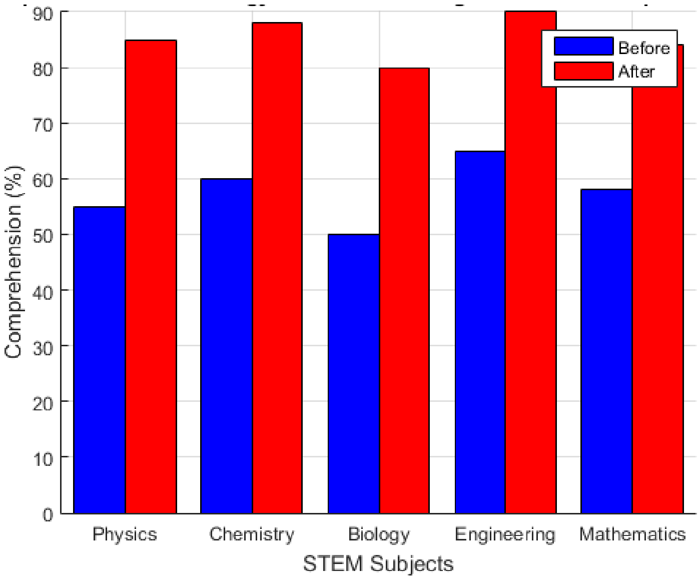

Fig. 4 A bar chart associating student comprehension after and before applying nanotechnology-based learning active strategies

about the subject of nanotechnology before and after the course. The graph demonstrates that interest of the participants has grown considerably in all aspects, though the highest growth rate has been noticed in aspects such as “Interest in Nanotechnology” and “Understanding of Key Concepts.” Participants self-reported pre-course interest as being approximately 35% to 50% whereas post course interest was measured at between 75% and 85%. This significant added value also suggests that active learning strategies enhance students’ interest and improve the understanding of nanotechnology.

Fig. 2 presents the comprehension scores of the students for the ten weeks by the topics covered. Overall the surface reveals that there is gradual improvement of comprehension scores with time and the added number of topics. This suggest that the more light is shed to student the more the extent of comprehension is gained. Of greater significance, is the finding that all the coefficients were positive and revealed that it took time for the students to comprehend the contents being taught. The increase in the plot is due to weeks in which students are exposed to some difficult or interesting material.

Fig. 3 shows class participation rates measured on the same ten weeks’ dependent variable. The results are that the participation rates are al to have been increasing, from 45% to an incredibly high 90%. The overall increase suggests that students found themselves shift in a progressive manner more as willing participants and contributors in our class discourses as the course unfolded. The increase in participation towards the last couple of weeks most likely correlates with an increase in student competence in comprehending and approaching unfamiliar or difficult issues likely encouraged by the active engagement strategies used throughout the course.

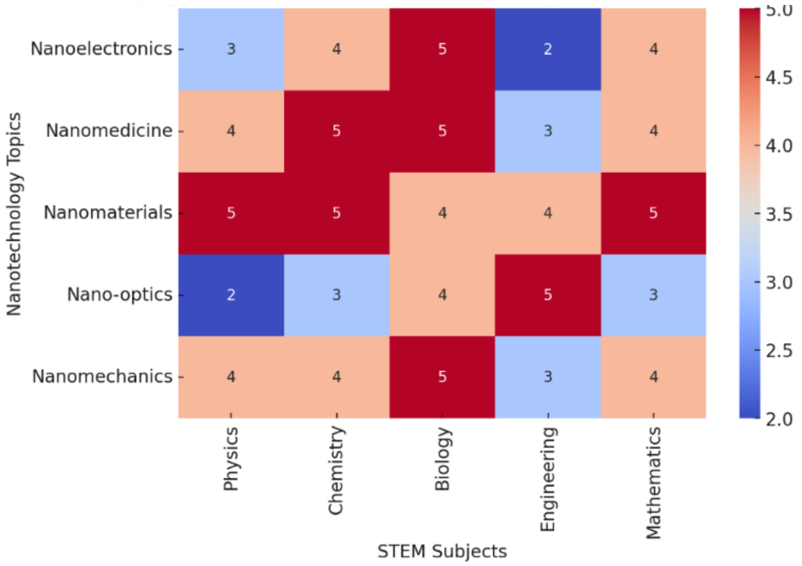

Fig. 5 A heatmap presentation student engagement levels versus various nanotechnology topics in STEM education

Fig. 4 utilizes a bar chart to demonstrate how students achieved enhanced comprehension levels in STEM subjects when nanotechnology-based active learning methods were utilized. The intervention began with moderate student comprehension between 50% and 65% according to pretest results. Student comprehension levels underwent a substantial increase after implementation as measurement results indicate an 80%–90% understanding in every subject. The combination of nanotechnology principles within hands-on learning methods leads to improved student retention in STEM subjects and stronger academic comprehension across all subjects. The research utilizes a bar chart to demonstrate how students achieved enhanced comprehension levels in STEM subjects when nanotechnology-based active learning methods were utilized. The intervention began with moderate student comprehension between 50% and 65% according to pretest results. Student comprehension levels underwent a substantial increase after implementation as measurement results indicate an 80%–90% understanding in every subject. The combination of nanotechnology principles within hands-on learning methods leads to improved student retention in STEM subjects and stronger academic comprehension across all subjects. The research utilizes a bar chart to demonstrate how students achieved enhanced comprehension levels in STEM subjects when nanotechnology-based active learning methods were utilized. The intervention began with moderate student comprehension between 50% and 65% according to pretest results. Student comprehension levels underwent a substantial increase after implementation as measurement results indicate an 80%–90% understanding in every subject. The combination of nanotechnology principles within hands-on learning methods leads to improved student retention in STEM subjects and stronger academic comprehension across all subjects.

The visualization tool shows students' levels of engagement consisting of values from one to five for different nanotechnology subjects within STEM domains. The combination of nanoelectronics and nanomaterials receives high student interest throughout majority of subject areas because of their practical application potential. The engagement with nano-optics and nanomechanics reveals moderate fluctuation among students from biology and chemistry majoring classes. These observations enable teachers to organize their teaching approach by using interesting material from highly popular subjects as well as interactive teaching methods to boost student engagement in less popular areas.

4. Conclusions

It will be important to note from the various results culminated in the present figures that the implementation of nanotechnology in STEM education with both active learning techniques enhanced levels of student achievement. As Fig. 1 also shows, post-course metrics of the student interest in nanotechnology was significantly higher before starting with 35-50% and jumped to 75-85% which shows that the active learning methods were engaging the students. Comprehension results show improved performance over the ten-week course, further evidencing the value of extended learning in challenging concepts. Also, it focuses on class participation rates that have risen from 45% to 90% which indicates cordiality and callousness from students to participate in class discussions. Taken together, these findings show how active learning paradigms contribute towards improving interest, understanding, and engagement in STEM material and offer important direction for future utilization of active learning strategies in emerging sciences.

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