

# The Impact of Nanotechnology Applications on the Performance of Civil Engineering Projects: A Field Study in Iraq

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## ABSTRACT

The construction sector in Iraq continues to experience significant challenges related to cost overruns, schedule delays, quality deficiencies, safety risks, and weak sustainability performance, largely due to reliance on conventional materials and practices. In this context, nanotechnology has emerged as a promising innovation with the potential to enhance construction materials and improve overall project outcomes; however, empirical evidence from developing countries remains limited. This study examines the impact of nanotechnology applications on the performance of civil engineering projects in Iraq using a quantitative approach. Data were collected through a structured questionnaire distributed to 250 construction professionals, including engineers, project managers, consultants, and academics. The perceived effects of nanotechnology adoption were assessed across five performance dimensions: time, cost, quality and durability, safety and health, and sustainability. Statistical analysis using SPSS included descriptive statistics, reliability testing, the Relative Importance Index (RII), and multiple regression analysis. The results indicate that cost and time performance are the most significant perceived benefits, followed by quality and durability, while safety, health, and sustainability also show substantial importance. The regression model demonstrates strong explanatory power ( $R^2 = 0.886$ ,  $p < 0.001$ ), with cost performance emerging as the strongest predictor of overall project performance. The findings suggest that nanotechnology is a strategic tool for enhancing efficiency and long-term value in civil engineering projects in developing-country contexts.

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## 1. INTRODUCTION

The construction industry is considered one of the most important economic sectors in Iraq, as it has a direct impact on various aspects of the community [1], civil engineering industry is one of the pillars of national growth especially in the developing world like Iraq, where the essential infrastructure needs to be rebuilt, developed and enhanced with better capacity in response to the socio-economic needs. In spite of heavy investments, numerous constructions work in Iraq are still affected by chronic problems, such as time delays, cost increase, poor quality, safety, and poor sustainability results [2]. These issues are usually linked to traditional construction material and the conventional practice that is not keeping up with the modern performance needs due to the high pace of urbanization and environmental pressures, so nanotechnology has become a revolution in the field of civil engineering and it presents the possibility of transforming construction materials, construction processes and the performance of the infrastructure. Nanotechnology provides an opportunity to manipulate and control matter at the nanoscale, and thus, design materials and systems with improved or even new properties, which has a direct effect on the quality,

durability, and sustainability of civil engineering projects [3,4]. Nano-silica, nano-titanium dioxide, carbon nanotubes, and other nanomaterials incorporated into existing construction materials (i.e., concrete, cement, steel, and coating) have shown great improvement in mechanical strength, durability, and multifunctionality [5-8]. With the ability to introduce materials with more desirable mechanical properties, increased strength, and cost-effectiveness [9]. To boost overall performance, recent focus has shifted towards addition of nanoscale to conventional building materials. Among the most important developments, one can distinguish the development of high-performance and nano-modified construction materials that are more resilient and powerful, as well as less harmful to the environment [3,7]. Nanotechnology makes it possible to create multifunctional materials that are capable of self-cleaning, self-repairing, self-sensing, and self-healing, thus increasing the service life of civil infrastructure and lowering the cost of maintenance [6,10,11]. Nanomaterials are also used to make building elements lighter, stronger and more energy efficient and enable the pursuit of sustainable building practices [5,7,12]. Research conducted in the year 2015-2023 points out that the addition of nano-based elements which give better mechanical strength to concrete, steel and composite materials change the traditional materials of concrete, steel and composite materials [13] and the recent experimental studies have presented solid evidence on the effectiveness of self-healing of cement-based materials enabled by nanotechnology. Fahimizadeh et al. [14] designed a multifunctional, sustainable, and biological non-ureolytic self-healing system which showed a substantial increase in the efficacy of cementitious composites in terms of crack healing, durability, and long-term performance. This is evidenced by their results that prove high-order self-healing processes have the capability to prolong the service life of concrete structures and minimize the maintenance requirements, thus enhancing lifecycle performance of a civil engineering project. Nevertheless, the large-scale use of nanotechnology in civil engineering has not been an easy task, even despite the described positive outcomes, as the solution is expensive, has problems in terms of scaling, and it still requires additional research to be deemed safe to the environment and to people [4,6,15]. However, it is the current advancement and use of nanotechnology that should be critical in overcoming the shortcomings of traditional construction materials and practices that, in the long run, improves the performance and sustainability of civil engineering projects all over the planet [7,15]. In this regard, a gap in the research is created by a paucity of empirical field data assessing and quantifying the actual effect of the use of nanotechnology on the performance of civil engineering projects in Iraq. Thus, the goal of the given study is to quantify and determine the impact of nanotechnology implementation on the project performance in terms of field data and the opinion of the practitioners. The study concentrates on the main performance indicators, which include cost-effectiveness, structural performance, safety, and long-term sustainability, and hence the study is an addition to a better insight into the way nanotechnology can be used to overcome the urgent problems of civil engineering projects in Iraq. The paper is structured as follows: Section 2 presents the Literature Review, which covers the concept of nanotechnology, its applications in civil engineering (including concrete, roads and bridges, and construction materials), and its impact on civil engineering project performance. Section 3 describes the Research Methodology, including the research design, research instrument, questionnaire structure, study population and sample, data collection procedure, data analysis methods, and ethical considerations. Section 4 discusses the Results and Discussion, covering respondents' background characteristics, reliability analysis, recognition and implementation of nanotechnology, the impact of nanotechnology on time, cost, quality and durability, safety and health, and sustainability, as well as overall impact and acceptance, quality practices and barriers, and the multiple regression analysis. Section 5 presents the Conclusion.

## 2. LITERATURE REVIEW

### 2.1. Concept of Nanotechnology

Generally, Nanotechnology can be defined as the design, characterization, manufacturing, and/or use of structures, devices, and systems through the regulation of shape and size on a nanometer scale (1-100 nanometers (nm)) [16-19] (Ramsden, 2 Nano means a billionth of a meter ( $10^{-9}$  m), and nanotechnology is the science of handling matter at nanoscale in a way that takes advantage of size- and structure-specific properties and phenomena previously unavailable to individual atoms, molecules, or bulk materials [18,20].

#### A number of official definitions involve:

- National Nanotechnology Initiative (NNI) defines nanotechnology as the comprehension and manipulation of matter at the size scale of between about 1 and 100 nm, at which distinct phenomena make possible new uses. It is the imaging, measuring, modeling and manipulation of matter at this length scale [17].
- According to the International Organization of Standardization, it is the use of scientific knowledge to manipulate and control matter on the nanoscale to use size- and structure-dependent properties [20].
- The US Foresight Institute defines nanotechnology as a set of new technologies where structure of matter is manipulated on nanometer scale to create new materials and new devices with useful and distinctive properties [21].

- According to the Federal Ministries of Education and Research, Germany (BMBF), nanotechnology refers to the testing, application, and production of structures, molecule materials, and systems whose dimension or production tolerance is usually less than 100 nm [22].
- Other definitions focus on manipulation of materials at the atomic or molecular scale, in particular, to construct microscopic devices, and on the construction and utilization of structures, devices, and systems with new properties and functions because of their small size [23].

## 2.2 Applications of Nanotechnology in Civil Engineering

### 1. Nanotechnology in Concrete

- Nanomaterials, and in particular nano-silica, are commonly used to increase the mechanical property of cement matrices to attain better compressive and flexural strengths, lower porosity, and higher resistance to corrosion and environmental degradation [24].
- Studies have demonstrated that cement can be strengthened and made to last longer using nanomaterials especially nano-silica to replace up to 5 percent of the cement in reactive powder concrete (RPC) and self-compacting concrete (SCC) [25].
- Compressive and flexural strengths have also risen significantly and nano-silica and carbon quantum dots (CQDs) can be added to cement-based materials but CQDs have increased to the levels of 72 % and 59 % at optimum dosages [24].
- Nanoparticles act as fillers and catalysts, refining the pore system, densifying the interfacial transition zone, and promoting the formation of additional calcium-silicate-hydrate (C-S-H) gel, which contributes to a denser and more durable concrete matrix [26].
- The use of nano-silica in concrete bricks and blocks has been shown to enhance compressive and flexural strengths, especially when combined with recycled materials and alternative curing methods [28].
- Nano-silica enhances strength and durability, but may lead to decreased workability and higher water requirements in concrete mixes, which requires proper proportioning and mix design [26].
- The longevity of concrete materials is enhanced by nanomaterials in two aspects, namely, enhancing their resistance to permeability, and resistance to corrosion. The compact and porous structure of the cement matrix and dispersion is highly associated with the corrosion resistance and permeability resistance of cement-based products [27]. Figure 1 demonstrates the system of the nano-engineered concrete.
- The Self-compacting lightweight aggregate concrete (SCLC) has incorporated the use of treated lightweight aggregates and nano-silica that have led to enhanced fluidity, passing and segregation resistance [29].
- Nanotechnology enables the production of higher-quality cement with reduced quantities, thereby lowering CO<sub>2</sub> emissions from cement factories and contributing to more sustainable construction practices [30].
- The Nanomaterials are also used as geopolymer composites replacing conventional Portland cement, this decreases carbon footprint and energy used in making concrete even further [31].

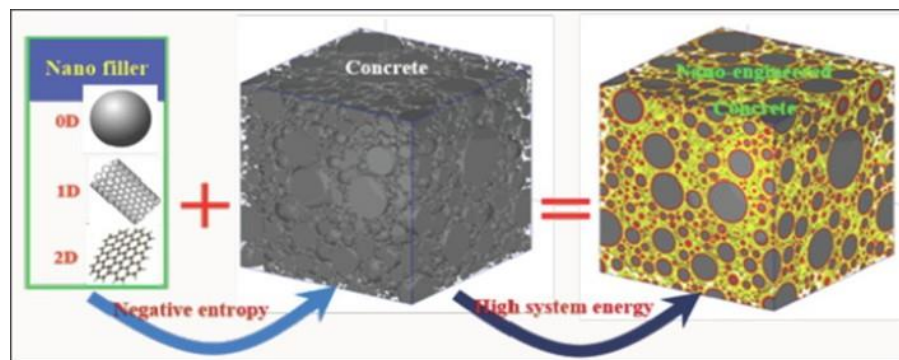


Figure 1. Nano-engineered concrete [32].

### 2. Nanotechnology in Roads and Bridges

- Nano clay, nano silica, carbon nanofiber, and nano titanium dioxide are nanomaterials that have been employed to enhance the rheological and mechanical properties of bitumen and asphalt mixtures, to make them more resistant to traffic loads and environmental factors [33].

- Nanomaterials have been widely used in asphalt mixtures to improve rutting resistance, fatigue life, and temperature sensitivity. You *et al.* [34] demonstrated that nano-clay modified asphalt exhibits better mechanical performance and longer service life compared to conventional asphalt mixtures.
- Nanotechnology in Construction Materials
- Nanotechnology is also applied in coatings, steel, glass, and insulation materials. Nano-coatings provide self-cleaning, anti-corrosion, and water-repellent properties, which contribute to extending the service life of buildings and infrastructure [35].
- In steel structures, nanotechnology improves resistance to corrosion and fatigue, which is particularly important in harsh environmental conditions [35].

Figure 2 indicates how the successful application of nanotechnology product in the construction industry in the different application areas is likely to happen. As indicated in the figure, nanotechnology applications in construction materials will have a wide implementation in the short-term (less than five years). This is an indication of the maturity and technological preparedness of nano modified concrete, coatings and additives which are relatively high. On the other hand, the applications of nanotechnology related to sustainability, safety and health and intelligent sensing systems are expected to have lengthy implementation processes. The causes of this delay include increased initial cost, standards and regulation issues, and increased technological complexity. On the whole, the figure points out that the introduction of nanotechnology in the construction industry will be incremental with material-based application being at the forefront in the introduction of more advanced and integrated nano-enabled construction systems [36].

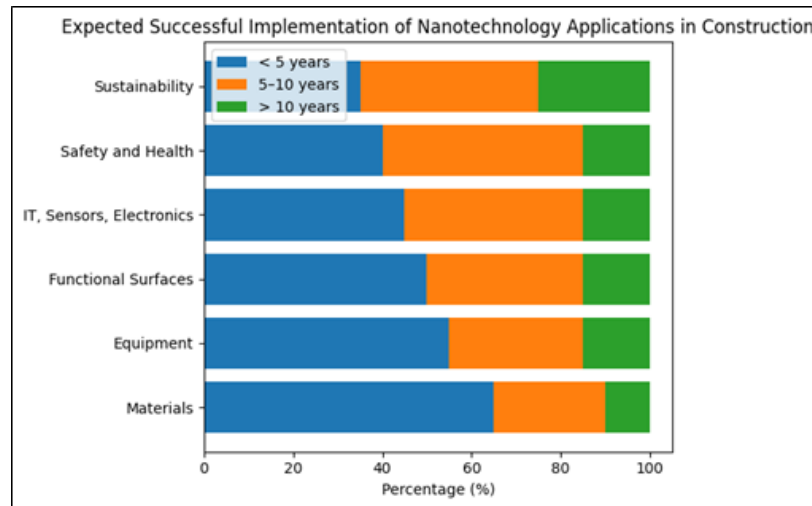


Figure 2. Expected Timeline for Successful Implementation of Nanotechnology Applications in the Construction Sector [36].

### 2.3 Impact of Nanotechnology on Civil Engineering Project Performance

The following Table 1 synthesizes the key impacts of nanotechnology on civil engineering project performance, as reported across all relevant paragraphs. The impacts are grouped into major themes: Material Performance, Structural Monitoring & Functionality, Environmental Sustainability, Economic & Lifecycle Effects, and Implementation Challenges.

Table 1. Synthesizes the key impacts of nanotechnology on civil engineering project performance.

| Impact Area                 | Key Findings   | References     |
|-----------------------------|--|----------------|
| <b>Material Performance</b> | 1. Compressive strength (up to 54%), flexural strength (up to 21%), and durability of concrete and cementitious composites is improved by nanomaterials (e.g., nano-silica, nano-TiO <sub>2</sub> , carbon nanotubes, multi-layer graphene). | [3,10,37,38,5] |
|                             | 2. Nano-modified substances have better strength and durability, better acid and corrosion resistance and less water absorption.   |                |
|                             | 3. Nano-silica and nano-TiO <sub>2</sub> give building materials self-cleaning and polluting reducing properties.  |                |
|                             | 4. Nano-CaCO <sub>3</sub> enhances compressive strength and densification of concrete bricks (up to 35.25 MPa compared with 21 MPa of conventional bricks).  |                |

|  |   |           |
|--|---|-----------|
|  | 5. Nanoproducts have the ability to hasten cement hydration and pozzolanic reactions and result in more compact microstructures and resistance to chemical attacks.   |           |
| <b>Structural Monitoring &amp; Functionality</b> | 1. Embedded nano sensors enable real-time structural health monitoring, increasing maintenance efficiency and safety.<br>2. Nanotechnology enables functionalities such as self-healing, self-sensing, self-vibration damping, and self-repairing in construction materials.<br>3. Nanomaterials (e.g., carbon nanotubes) contribute to crack prevention and improved seismic resilience.   | [10,6,15] |
| <b>Environmental Sustainability</b>              | 1. Nanotechnology integration can reduce carbon emissions by up to 30% and improve energy performance by 25%.<br>2. The nano-enhanced materials contribute to sustainable construction such as cutback of pollution and better lifecycle performance.<br>3. With the use of nanomaterials, the cement can be reduced, thus reducing the CO <sub>2</sub> footprint, NO <sub>x</sub> 65 -80% in 1h (Orange II dye 18 -50% in 9h), and degradation of pollutants using nano-TiO <sub>2</sub> . | [38,5,15] |
| <b>Economic &amp; Lifecycle Effects</b>          | 1. Nanotechnology will reduce maintenance costs because of better durability and self-repairing nature.<br>2. Outputs are improved with regard to material performance and energy efficiency, which results in reduced lifecycle costs and enhanced competitiveness.<br>3. Economic implications are a potential cost hindrance owing to excessive initial material expenditures, but it is expected to reduce in the future.   | [6,7,15]  |
| <b>Implementation Challenges</b>                 | 1. The barriers to large-scale adoption still persist: The costs, regulatory compatibility, long-term safety, and the necessity to conduct more research on the impact on the environment and human health.<br>2. The amount of nanomaterial to be added is also vital; too much content will reduce mechanical properties.<br>3. The tendency of agglomeration of nanoparticles demands complex mixing and dispersing methods.   | [6,15,39] |

The implications of nanotechnology on the civil engineering project performance are summarized in Table 2 below on six dimensions, including time, cost, quality, durability, safety, and sustainability.

Table 2. Combining the impacts of Nanotechnology Results in Time, Cost, Quality, Durability, Safety, and Sustainability in Civil Engineering Works.

| Performance Aspect    | Impact of Nanotechnology   | References   |
|-----------------------|--|--------------|
| <b>Time</b>           | 1. Increased speed of construction.<br>2. Improved ease of mixing, rate of setting, and workability.   | [3,37,35]    |
| <b>Cost</b>           | 1. Potential for reduced maintenance costs.<br>2. High initial material costs, but projected to decrease.<br>3. Reduced life cycle costs due to increased durability.                                      | [6,8,40]     |
| <b>Quality</b>        | 1. Enhanced strength, durability, and lightness of building materials.<br>2. Improved mechanical properties (compressive, flexural, tensile, impact strength).<br>3. Multifunctional coatings and sensors. | [3,40,5]     |
| <b>Durability</b>     | 1. Significant improvement in material durability.<br>2. Reduced porosity and increased resistance to corrosion.<br>3. Extended lifespan of structures.  | [37,10,41]   |
| <b>Safety</b>         | 1. Improved structural health monitoring via nano sensors.<br>2. Enhanced fire and corrosion resistance.<br>3. Increased seismic resilience.   | [6,7,15]     |
| <b>Sustainability</b> | 1. Reduced carbon emissions (up to 30%).<br>2. Conservation of resources and minimization of waste.<br>3. Improved energy performance (up to 25%).<br>4. Eco-efficient materials and methods.              | [37,7,15,42] |

### 3. METHOD

The research methodology assumed in the study was quantitative research methodology, which used a structured questionnaire as a way of collecting and analyzing data. The general study process is depicted in Flowchart Figure 3 that describes each step of the study design to analysis.

#### 3.1 Research Design

This paper focuses on the application of a field survey research design as a quantitative research design to investigate how nanotechnology application affects the performance of civil engineering projects in Iraq. The quantitative approach is appropriate as it enables the systematic measurement of respondents' perceptions using numerical data and supports statistical analysis of the relationships between nanotechnology applications and project performance dimensions.

### 3.2 Research Instrument

A structured survey questionnaire that was designed to collect data specially through extensive literature review was used in the collection of data. The questionnaire was to be used to gauge the perceived effects of the applications of nanotechnology on the performance of civil engineering projects.

To achieve consistency in the response and make the results subject to quantitative statistical analysis, all the questions in the questionnaire were scaled to a five-point Likert scale, with 1 = Strongly Disagree, and 5 = Strongly Agree. The questionnaire also investigates barriers and quality related issues involved in the adoption of nanotechnology in the civil engineering projects. This part analyses the perceived effect of cost, standards, safety concerns and institutional support in a five-point Likert scale. The answers to this section were evaluated with the help of a five-point Likert scale, with 1 = Not influential at all, to 5 = Very influential, where the respondents were able to rate how much each factor is a barrier to the implementation of nanotechnology.

### 3.3 Questionnaire Structure

The questionnaire was developed based on relevant previous studies. The questionnaire has been designed into five key sections which aimed to respond to a particular aspect of the research objectives concerning the use of nanotechnology in civil engineering projects.

#### Part 1: Background Information of the respondents

In this section, general and professional data of the respondents is gathered as job position, engineering specialization, years of experience, project type, project location, and the degree of nanotechnology application in their projects. The attributes of the study sample were described using this information.

#### Section Two: Recognition and Implementation of Nanotechnology

This part evaluates the awareness, knowledge and adoption of nanotechnology application in the professional practice of the respondents. It consists of training, technical preparedness, organizational support, and perceived competitive advantages of nanotechnology utilization items.

#### Part Three: The Nanotechnology Impact on Performance of the Project

This section assesses the perceived impact of the nanotechnology applications to the performance of civil engineering projects in five major dimensions:

- Time performance.
- Cost performance.
- Quality and durability.
- Safety and health.
- Sustainability.

Everything under this section was measured with five-point Likert scale of 1 = Strongly Disagree to 5 = Strongly Agree.

#### The fourth section: The overall impact and acceptance

This part discusses the perception of the respondents on the overall effects of the application of nanotechnology, such as the satisfaction level of the stakeholders, value added over the conventional processes, compatibility with innovation strategies, and improvement in project competitiveness.

#### Section Five: Quality Practices and Barriers

In this section, the barriers and quality-related issues that might impede the implementation of nanotechnology in the civil engineering projects are identified. The answers in this section were gauged on a five-point liker scale, 1 = Not influential at all to 5 = Very influential, to determine the extent to which each of the factors is a barrier to successful implementation.

### 3.4 Study Population and Sample

The population of the study is the professionals of the construction and engineering industry in Iraq who represent various engineering and technical fields. These are the project managers, engineers of several different specializations, consultants, contractors, and academics engaged in the planning, design, execution, and management of construction projects.

The questionnaire will be performed focusing on those respondents that have firsthand professional experience or have adequate technical knowledge covering construction projects and the use of nanotechnology in the built environment. Non-probability purposive sampling was chosen in order to make sure that the subjects possess pertinent experience and professional exposure that would be fitting within the goals of the research. Out of these 250 valid responses were received and incorporated into the final dataset to be analyzed statistically. This is deemed a sufficient sample size to conduct a quantitative analysis and generate valid and useful findings.

### 3.5 Data Collection Procedure

The survey was conducted in a two-fold data collection method. Some of the data were gathered via paper-based questionnaires that would be distributed directly to respondents in construction sites, offices, and academic

institutions, with the rest of the responses being gathered electronically by use of Google Forms. This mixed method also helped to reach more respondents in various Iraqi provinces and made the data collection process more efficient and complete. All the responses gathered served only academic research purposes and the information of respondents was kept confidential.

### **3.6 Data Analysis Methods**

The collected data were analyzed using the Statistical Package for the Social Sciences (SPSS), version 2022. Several statistical techniques were employed to achieve the objectives of the study, as outlined below:

1. Descriptive statistics, including frequencies, means, and standard deviations, were used to summarize respondents' demographic characteristics and to identify general trends in the collected data.
2. Reliability analysis was conducted using Cronbach's alpha to assess the internal consistency and reliability of the questionnaire items.
3. The Relative Importance Index (RII) was applied to rank the significance of nanotechnology applications, project performance dimensions, and identify barriers based on respondents' perceptions. This method enables the comparison and prioritization of factors according to their relative importance and is widely adopted in construction management and engineering research.
4. Lastly, the regression analysis (Multiple Regression Analysis) was conducted to determine the connection between nanotechnology applications and the civil engineering project performance dimension. It was based on this analysis to estimate the strength and direction of the influence of independent variables on the dependent variables as well as the predictive ability of the proposed research framework. Since data were collected using a self-reported questionnaire, common method bias may exist. To reduce this potential bias, respondents were assured of anonymity, items were clearly worded, and questionnaire sections were logically separated. In addition, multicollinearity was assessed using (VIF) and tolerance values.

### **3.7 Ethical Considerations**

The study has adhered to all the ethical tenets of academic research. All respondents were told about the purpose and extent of the study, and all answers were kept secret. A personal or identifying information was not gathered or revealed, and the data collected were used solely as academic research purposes.

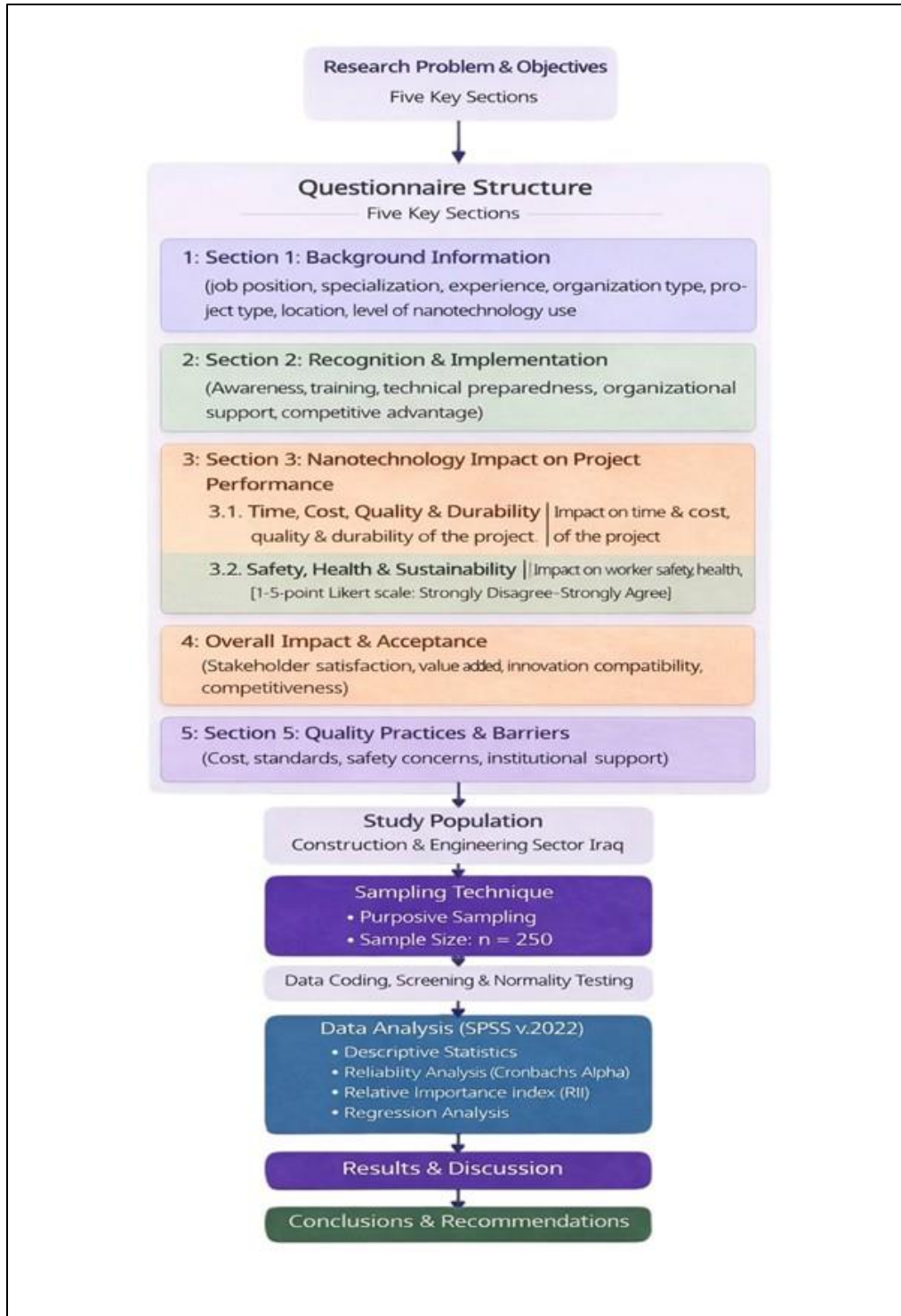


Figure 3. Flowchart of Research Methodology.

#### 4. RESULTS AND DISCUSSION

This The respondents' background characteristics of the study participants are shown in Table 3 and Figure 4. The distribution of participating professional roles, engineering specializations, years of experience, geographical locations, level use in nanotechnology, and nanotechnology types of application are presented in the table.

In terms of professional role, the results reveal that there was one group of respondents who were site engineers (41.04%) followed by academia and researcher professions (40.24%). Managers formed 10.36% of the sample and consultants 7.97%. This distribution reflects a good balance between practical and academic knowledge among the samples studied. With regard to the engineering branch of study, the majority (85.66%) were from civil engineering, while 13.94% specialized in nanotechnology. This also indicates the strong civil engineering aspect of the research work in addition to its specialized aspect (nanotechnology). In terms of years of experience, the highest percentage of participants (29.88) had a range of 6 to 10 years' experience then (25.10) years of other segments. The age group of 11-15 years existed in 19.52, 16-20 years (14.74) and over twenty years (10.36) respectively. This denotes that professionals who have diverse levels of experience, contrived majorly by moderate experience, make up the sample. In terms of the extent of the use of nanotechnology, the results found are that 47.01 per cent of the respondents stated that they used nanotechnology partially or in an experimental basis, and 43.43 per cent stated that they extensively used nanotechnology in their projects. This was only 9.16% of them who said they were not using nanotechnology. This implies that there is a comparatively high degree of involvement in the application of nanotechnology in civil engineering projects. Lastly, considering the type of nanotechnology application, the most widespread application was the nano-additives to concrete (55.78%), and the next one was the nano-coatings and corrosion resistance and moisture (27.09%). Less common were nano metal oxides (9.16%), nano-sensors used to monitor (7.57%). These results highlight that material enhancement applications dominate current nanotechnology practices in civil engineering projects, as nano-additives and protective coatings are widely adopted to improve mechanical strength, durability, and resistance to environmental degradation. This finding is consistent with previous studies, which reported that nano-silica, nano-alumina, and nano-coatings are among the most practical and cost-effective nanotechnology applications currently implemented in construction materials and infrastructure projects [43].

Table 3. Background Information of Respondents (n = 250).

| Variable                                  | Category  | Frequency | Percentage (%) |
|---|---|-----------|----------------|
| <b>Professional Role</b>                  | Site Engineer                                     | 103       | 41.04          |
|   | Academic / Researcher                             | 101       | 40.24          |
|   | Project Manager                                   | 26        | 10.36          |
|   | Consultant  | 20        | 7.97           |
|   | Total   | 250       | 100            |
| <b>Engineering Specialization</b>         | Civil Engineering                                 | 215       | 85.66          |
|   | Nanotechnology                                    | 35        | 13.94          |
|   | Total   | 250       | 100            |
| <b>Years of Experience</b>                | Less than 5 years                                 | 63        | 25.10          |
|   | 6–10 years  | 75        | 29.88          |
|   | 11–15 years                                       | 49        | 19.52          |
|   | 16–20 years                                       | 37        | 14.74          |
|   | More than 20 years                                | 26        | 10.36          |
|   | Total   | 250       | 100            |
| <b>Level of Nanotechnology Use</b>        | Partially / Experimental Use                      | 118       | 47.01          |
|   | Extensive Use                                     | 109       | 43.43          |
|   | Not Used  | 23        | 9.16           |
|   | Total   | 250       | 100            |
| <b>Type of Nanotechnology Application</b> | Nano-additives for Concrete                       | 140       | 55.78          |
|   | Nano-coatings Resistant to Corrosion and Moisture | 68        | 27.09          |
|   | Nano Metal Oxides (e.g., TiO <sub>2</sub> )       | 23        | 9.16           |
|   | Nano-sensors for Monitoring                       | 19        | 7.57           |
|   | Total   | 250       | 100            |

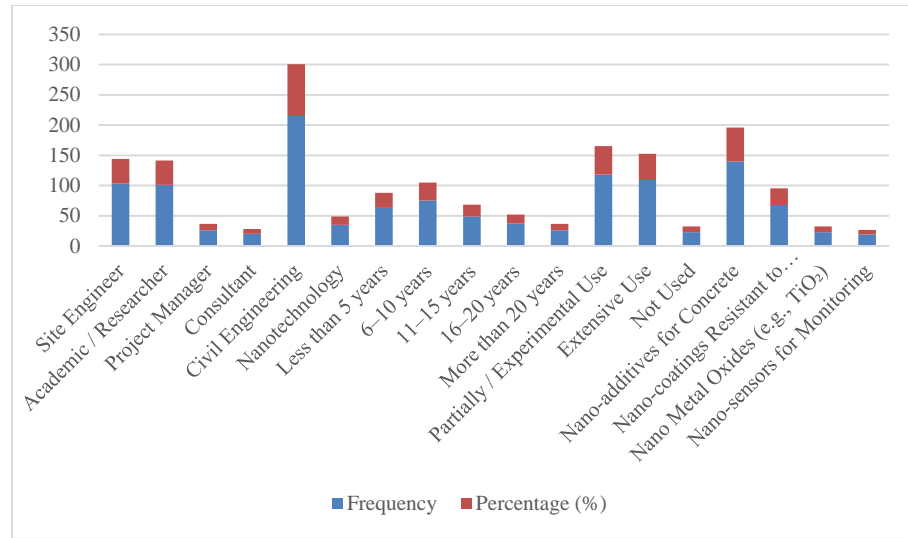


Figure 4. Background Information of Respondents (n=250).

The reliability analysis was performed through the use of Cronbach alpha coefficient on the major parts of the questionnaire and the results are presented in Table 4. This was done through analysis to determine the internal consistency of the measurement items in each of the constructs. The first section, the Nanotechnology recognition and Implementation section, comprises six items with a Cronbach’s alpha of 0.84, which is good reliability. This finding proves that the items in this section are very consistent and they measure the awareness, preparedness, and adoption among the respondents toward the application of nanotechnology in civil engineering practice. The Nanotechnology Impact on Project Performance section consists of twenty-nine questions, and the Cronbach alpha of 0.88 was obtained, which is very good. The high value indicated a high degree of internal consistency of the items used to measure the perceived effect of nanotechnology on time, cost, quality, safety, and sustainability performance of civil engineering projects. The overall Impact and Acceptance section, which consisted of four items, had a Cronbach alpha of 0.82, which is a good reliability. This shows that the items are always able to capture perceptions of the respondents to the overall benefits, acceptance, and strategic value of nanotechnology applications. Lastly, the Quality Practices and Barriers section, having seven items, had a Cronbach alpha coefficient of 0.86 as a representation of very good reliability. This finding supports the fact that the measures of quality-related practices and perceived obstacles to the implementation of nanotechnology are coherent and reliable.

Table 4. Cronbach’s Alpha Reliability Results for Questionnaire Constructs.

| Questionnaire Section        | No. of Items | Cronbach’s Alpha | Reliability Level |
|------------------------------|--------------|------------------|-------------------|
| Recognition & Implementation | 6            | 0.84             | Good              |
| Project Performance Impact   | 29           | 0.88             | Very Good         |
| Overall Impact & Acceptance  | 4            | 0.82             | Good              |
| Quality Practices & Barriers | 7            | 0.86             | Very Good         |

**Table 5** summarizes the respondents’ perception regarding nanotechnology in terms of frequency, mean score, standard deviation, Relative Importance Index (RII), and rank. The top-rated item suggests that the respondents are extremely convinced that nanotechnology gives a competitive advantage to projects (Mean = 4.05, RII = 81), followed by its ability to stimulate innovation opportunities (Mean = 3.98, RII = 80). There is moderate consensus between the knowledge of nanotechnology and its role in project success among respondents, with a generally positive but not all agreeing opinion. The technical capability of project teams is fifth in rank, implying that there is some restraint in applied integration capacity. The least ranked item involves organizational training and guidance which has a mean that is below the neutral point (Mean = 2.80, RII = 56), showing a sharp difference in institutional backing even when the general attitudes towards nanotechnology are positive.

Table 5. Recognition and Implementation of Nanotechnology: Descriptive Statistics, Frequencies, and (RII) Results (N = 250).

| Rank | Item | Strongly Disagree (1) | Disagree (2) | Neutral (3) | Agree (4) | Strongly Agree (5) | Mean | SD | RII% |
|------|------|-----------------------|--------------|-------------|-----------|--------------------|------|----|------|
|------|------|-----------------------|--------------|-------------|-----------|--------------------|------|----|------|

|   |   |    |    |    |     |    |      |      |    |
|---|---|----|----|----|-----|----|------|------|----|
| 1 | You believe that using nanotechnology gives the project a competitive advantage | 0  | 18 | 0  | 184 | 48 | 4.05 | 0.69 | 81 |
| 2 | You believe that nanotechnology increases opportunities for innovation          | 0  | 0  | 21 | 212 | 17 | 3.98 | 0.39 | 80 |
| 3 | You have sufficient knowledge of nanotechnology in my field of work             | 0  | 0  | 80 | 141 | 29 | 3.80 | 0.63 | 76 |
| 4 | You believe that using nanotechnology increases the chances of project success  | 27 | 0  | 22 | 162 | 39 | 3.74 | 1.07 | 75 |
| 5 | The project team has the technical ability to integrate nanomaterials           | 0  | 44 | 42 | 143 | 21 | 3.56 | 0.88 | 71 |
| 6 | Your organization has received training or guidance materials on nanotechnology | 31 | 55 | 98 | 66  | 0  | 2.80 | 0.97 | 56 |

Table 6 presents descriptive statistics, frequency of the responses, and (RII) result of the dimension of time performance of nanotechnology applications by the construction projects. The answers of 250 people will be reviewed on a five-point Likert scale with strongly disagree (1) and strongly agree (5). The results show that time related are predictors of moderate means with high that is, there is overall agreement among the respondents that the application of nanotechnology in project timing and efficiency in project implementation is positive. The (RII) was 67 to 84 with varying levels of significance being presented by the factors considered. The shortest factor was the decrease of the total period of project execution (RII = 84), which indicates that nanotechnology is crucial in hastening construction operations. This observation is in line with other studies that have indicated that nanotechnology-based materials can improve the speed of construction and mitigate delays due to increased performance of the materials, as well as minimize defects [35,44]. (Nanotechnology in Construction). The elimination of delays due to rework or repairs also goes to demonstrates how nanotechnology has helped to reduce the delays in terms of schedules. Even less important factors like minimizing downtime as a result of inspections or re-manufacturing and enhancing the effectiveness of the workforce continued to have moderate (RII) values, which raises the agreement among the respondents despite the variation in the perceptions of the same. All in all, the results prove that nanotechnology plays a significant part in enhancing the project time performance in accelerating the process, minimizing delays and aiding in controlling the schedule better.

Table 6. Impact of Nanotechnology on Project Time Performance: Descriptive Statistics, Frequencies, and (RII) Results (N = 250).

| Rank | Item  | Strongly Disagree (1) | Disagree (2) | Neutral (3) | Agree (4) | Strongly Agree (5) | Mean  | SD    | RII% |
|------|---|-----------------------|--------------|-------------|-----------|--------------------|-------|-------|------|
| 1    | Nanotechnology helped reduce the overall project execution duration | 0                     | 0            | 21          | 164       | 65                 | 4.176 | 0.561 | 84   |
| 2    | Nanotechnology reduced delays caused by rework or repairs           | 0                     | 0            | 69          | 159       | 22                 | 3.812 | 0.574 | 76   |
| 3    | Nanotechnology accelerated the completion of critical activities    | 0                     | 16           | 27          | 207       | 0                  | 3.764 | 0.556 | 75   |
| 4    | Nanotechnology improved adherence to the planned project schedule   | 0                     | 0            | 95          | 135       | 20                 | 3.700 | 0.609 | 74   |
| 5    | Nanomaterials reduced downtime due to inspections                   | 30                    | 0            | 64          | 134       | 22                 | 3.472 | 1.072 | 69   |

| or re-manufacturing |   |    |    |    |    |    |       |       |    |
|---------------------|---|----|----|----|----|----|-------|-------|----|
| 6                   | Nanotechnology improved workforce efficiency by reducing execution time | 21 | 50 | 49 | 87 | 43 | 3.324 | 1.214 | 67 |

Table 7 shows the descriptive statistics, frequency distribution, and (RII) findings of the cost performance dimension of nanotechnology applications in construction projects. This is analyzed on the basis of the responses of 250 respondents, and the responses on the five-point Likert scale (strongly disagree (1) to strongly agree (5)). The analysis shows that the mean values and (RII) values of the cost performance factors were moderate to high (3.47-4.18) and (69-84), respectively, and respondents had a high perception that nanotechnology has a positive impact on the cost performance of a project. These findings are consistent with previous studies have shown that nanotechnology-enhanced materials have the capability of considerably lowering the construction costs due to their increased resistance to wear, a decrease in material wastages, and an increased lifespan of the structures [8,44,45]. The most influential factor was the minimization of material waste in the course of project implementation (RII = 84), with the focus on the benefits of nanotechnology in terms of the cost of operations. The outcome is in line with previous studies, which suggest that, due to the high efficiency of nanomaterials, the quantity of waste produced during construction is minimized, resulting in decreased direct and indirect project costs [46]. On a similar note, the ranking of reduced rework and expensive repair was high, which confirms conclusions made by other researchers who observed that nanotechnology improves the quality and performance of materials, thus reducing defects and corrective works [47]. Moreover, the variables pertaining to long-term economic value addition and the life-cycle cost reduction showed relatively high (RII) values, which supports the previous literature that narrates that nanotechnology application can lead to a decrease in the maintenance needs and enhance the cost-effectiveness of the construction project throughout the life cycle. The value-for-money benefits presented in past studies on sustainable and high-performance construction materials can also be found in the improvement of the cost-to-quality ratio [47]. Overall, the findings of Table 7 results are highly consistent with the existing literature, as it confirms that nanotechnology has had a significant impact on the cost performance of the project in terms of waste reduction, cost of re-work and maintenance, and efficiency of resources in the project life cycle.

Table 7. Impact of Nanotechnology on Project Cost Performance: Descriptive Statistics, Frequencies, and (RII) Results (N = 250).

| Rank | Item  | Strongly Disagree (1) | Disagree (2) | Neutral (3) | Agree (4) | Strongly Agree (5) | Mean  | SD    | RII% |
|------|---|-----------------------|--------------|-------------|-----------|--------------------|-------|-------|------|
| 1    | The application of nanotechnology helped reduce material waste during project execution.              | 0                     | 0            | 21          | 164       | 65                 | 4.176 | 0.561 | 84   |
| 2    | The use of nanotechnology reduced the need for rework or costly repairs.                              | 0                     | 0            | 69          | 159       | 22                 | 3.812 | 0.574 | 77   |
| 3    | Nanotechnology techniques contributed to reducing the total project cost over the project life cycle. | 0                     | 0            | 52          | 198       | 0                  | 3.792 | 0.407 | 76   |
| 4    | Nanotechnology techniques provided long-term economic benefits by reducing maintenance requirements.  | 0                     | 16           | 27          | 207       | 0                  | 3.764 | 0.556 | 75   |
| 5    | Nanomaterials improved the efficiency of resource consumption (raw materials and energy).             | 0                     | 0            | 95          | 135       | 20                 | 3.700 | 0.609 | 74   |
| 6    | The use of nanotechnology contributed to improving the quality-to-cost ratio in the project.          | 30                    | 0            | 64          | 134       | 22                 | 3.472 | 1.072 | 69   |

Table 8 indicates the results of the descriptive statistics, response frequency, and (RII) of the quality and durability dimension of nanotechnology applications in construction projects. The analysis is performed on the response of 250 participants in terms of a five-point Likert scale, with strongly disagree (1) and strongly agree (5) as the extremes. The findings provide that all the quality and durability-related variables obtained moderate to high mean values, which prove the fact that the respondents agreed that nanotechnology can dramatically improve the construction quality and its long-term efficiency. The index values, (RII) are between 68 and 81, which implies that perceived factors are considered to increase the quality and durability. The first of the factors ranking highest was the enhancement of the accuracy and quality of project finishing works (RII = 81), and this pointed to the application of nanotechnology in influencing the construction precision and finishing standards. The enhancement of mechanical properties of construction materials was also among the ranks of improvement, which is partly linked to the efficiency of nanotechnology in strengthening and promoting the performance aspects. The results are in accordance with earlier investigations that have found that the nanotechnology-enhanced materials increase the strength, durability, and deterioration resistance mechanisms of materials [3,47]. Other criteria, like decreasing the number of defects during and after construction, increasing the resistance to the chemical attacks, increasing the corrosion resistance, and increasing the service life had rather high (RII) values. This shows that there is a high level of agreement between the respondents on how nanotechnology has been used in enhancing longevity and minimizing the long-term maintenance. In general, the findings suggest that nanotechnology is crucial in advancing the quality and durability of any construction through the enhancement of material characteristics, reduction of defects, and increase of resistance to environmental and chemical conditions.

Table 8. Impact of Nanotechnology on Project Quality and Durability Performance: Descriptive Statistics, Frequencies, and (RII) Results (N = 250).

| Rank | Item   | Strongly Disagree (1) | Disagree (2) | Neutral (3) | Agree (4) | Strongly Agree (5) | Mean  | SD    | RII% |
|------|--|-----------------------|--------------|-------------|-----------|--------------------|-------|-------|------|
| 1    | Nanotechnology improved the accuracy and quality of the project's finishing works                          | 0                     | 24           | 0           | 162       | 64                 | 4.064 | 0.799 | 81   |
| 2    | Nanotechnology improved the mechanical properties of construction materials (compressive/tensile strength) | 0                     | 0            | 66          | 164       | 20                 | 3.816 | 0.558 | 76   |
| 3    | Nanotechnology reduced defects and technical problems during and after construction                        | 22                    | 0            | 49          | 152       | 27                 | 3.648 | 0.988 | 73   |
| 3    | Nanomaterials enhanced resistance to chemical attacks (e.g., sulfates and salts)                           | 21                    | 0            | 40          | 173       | 16                 | 3.652 | 0.929 | 72   |
| 4    | Nanotechnology improved corrosion resistance in concrete and steel structures                              | 29                    | 0            | 46          | 154       | 21                 | 3.552 | 1.056 | 71   |
| 5    | Nanomaterials contributed to extending the service life of structures                                      | 0                     | 54           | 43          | 135       | 18                 | 3.468 | 0.910 | 69   |
| 6    | Nanotechnology helped reduce concrete permeability and increase resistance to environmental factors        | 22                    | 0            | 98          | 109       | 21                 | 3.428 | 0.972 | 68   |

The findings in Table 9 show that the majority of the safety- and health-related factors have a moderate to high mean, which can be interpreted as the agreement of the respondents that nanotechnology positively influences the improvement of workplace safety and health conditions. The values of (RII) are between 63 and 81 and show that the perceived importance of the factors examined differs. The most significant criterion can be linked to the safe environmental and health behavior of nanomaterials during handling (RII = 81), indicating the significance of the material safety when using nanotechnology in construction projects. This result cannot be contradicted by the earlier

research, which underscored that the safe usage of nanomaterials, along with the proper handling practice, could lead to better occupational safety with a minimum of harm to the prospective health risks [7,48]. Sufficiency of protective measures in handling the nanoparticles was also rated high and contributed to the importance of adopting good safety management practices. The factors related to the minimization of accidents associated with corrosion or structural failure and enhancement of the general safety level at construction sites showed relatively high RII values, which may be regarded as evidence of nanotechnology making the construction process less dangerous. Nevertheless, the case of the working conditions betterment and the decrease in occupational risks demonstrated the lowest (RII) value, which is why more efforts might be necessary to make the best out of the safety benefits of using nanotechnology. In general, the results prove that nanotechnology can be used to improve the safety and health performance in construction works with the help of relevant safety procedures, protective measures, and risk management strategies.

Table 9. Impact of Nanotechnology on Project Safety and Health: Descriptive Statistics, Frequencies, and (RII) Results (N = 250).

| Rank | Item  | Strongly Disagree (1) | Disagree (2) | Neutral (3) | Agree (4) | Strongly Agree (5) | Mean  | SD    | RII% |
|------|---|-----------------------|--------------|-------------|-----------|--------------------|-------|-------|------|
| 1    | Nanomaterials used in the project were environmentally and health-safe during handling            | 0                     | 0            | 18          | 204       | 28                 | 4.040 | 0.428 | 81   |
| 2    | Adequate protective measures were provided when dealing with nanoparticles                        | 0                     | 26           | 22          | 184       | 18                 | 3.776 | 0.727 | 76   |
| 3    | Nanocoatings or nano-additives helped reduce accidents related to corrosion or structural failure | 0                     | 0            | 64          | 186       | 0                  | 3.744 | 0.437 | 75   |
| 4    | Nanotechnology applications improved overall safety levels at the construction site               | 0                     | 0            | 113         | 91        | 46                 | 3.732 | 0.753 | 74   |
| 5    | Nanotechnology improved working conditions and reduced occupational hazards                       | 0                     | 46           | 139         | 44        | 21                 | 3.160 | 0.820 | 63   |

The findings in Table 10 indicate that all the respondents have moderate to high mean values of all the factors related to sustainability, which shows that they generally agree that nanotechnology has a positive impact on the sustainability of the environment in construction projects. The values of (RII) are between 69 and 81, which proves that the assessed factors are viewed as significant contributors to sustainable project performance. The solution that contributes to green and sustainable buildings (RII = 81) was on the list of the most important ones, which underlines the role of nanotechnology in facilitating the environmentally friendly construction practices. This observation is in line with the earlier researches that have stressed the fact that nanotechnology contributes towards sustainability through lessened effects on the environment, resource efficiency as well as prolonging the service life of the structures [15,47]. The considerations that concerned the extension of the service life and rationalization of consumption of natural resources were also ranked highly since long term sustainability was an important aspect in the application of nanotechnology. The lower-ranked factors, e.g., the need to enhance energy-use efficiency and to decrease environmental impacts, also reported moderate (RII) values meaning that respondents generally agreed, but some diversified in their perceptions. On the whole, the results prove that nanotechnology is an important tool in enabling sustainable construction through sustainable building solutions, resource utilization, and ensuring the reduction of the environmental burden in the long run.

Table 10. Impact of Nanotechnology on Project Sustainability: Descriptive Statistics, Frequencies, and (RII) Results (N = 250).

| Rank | Item   | Strongly Disagree (1) | Disagree (2) | Neutral (3) | Agree (4) | Strongly Agree (5) | Mean  | SD    | RII% |
|------|--|-----------------------|--------------|-------------|-----------|--------------------|-------|-------|------|
| 1    | Nanotechnology provides solutions that support green and | 0                     | 24           | 0           | 162       | 64                 | 4.064 | 0.799 | 81   |

| sustainable buildings |  |    |    |    |     |    |       |       |    |
|-----------------------|--|----|----|----|-----|----|-------|-------|----|
| 2                     | Nanotechnology contributed to extending the service life of structures and reducing future maintenance | 22 | 0  | 49 | 152 | 27 | 3.648 | 0.988 | 73 |
| 2                     | Nanotechnology helped rationalize the consumption of natural resources                                 | 21 | 0  | 40 | 173 | 16 | 3.664 | 0.929 | 72 |
| 3                     | Nanotechnology reduced the environmental impact of the project (emissions and waste)                   | 29 | 0  | 46 | 154 | 21 | 3.552 | 1.056 | 71 |
| 4                     | Nanomaterials improved energy-use efficiency in the project  | 0  | 54 | 43 | 135 | 18 | 3.468 | 0.910 | 69 |

Figure 5 shows the interdependence of the five dimensions of project performance, which include the time performance, cost performance, quality and durability, and safety and health, and sustainability, which are affected by the applications of nanotechnology. The organization of the figure is based on (RII) findings received on the basis of the empirical data analysis, as nanotechnology has been taken as the pathogenic factor in the middle of the performance dimensions. The thickness and direction of the connections are a measure of the relative strength of impact, as shown by the (RII) values. The findings indicate that nanotechnology contributes positively across all evaluated domains, with the highest influence observed in cost performance (RII = 0.757), reflecting the technology’s role in minimizing material waste, reducing rework, and enhancing long-term economic efficiency. Time performance (RII = 0.742) and safety and health (RII = 0.740) also show strong impacts, suggesting that nanotechnology improves construction scheduling, accelerates critical activities, and enhances on-site safety conditions. The technology further demonstrates meaningful contributions to sustainability (RII = 0.734) by supporting resource conservation, reducing environmental impacts, and improving energy efficiency. Finally, its effect on quality and durability (RII = 0.731) highlights improvements in material performance, resistance to deterioration, and overall structural lifespan. In general, the figures depicted in the data confirm the synergetic impact of nanotechnology on the performance of projects. Increases in one dimension strengthen other areas, which result in collective gains towards efficiency, quality, safety, and sustainability in construction initiatives.

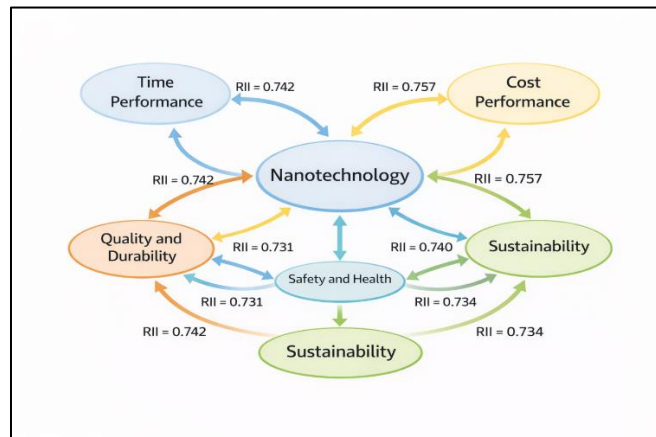


Figure 5. Interrelationship Between Time, Cost, Quality and Durability, Safety and Health, and Sustainability Performance Dimensions Influenced by Nanotechnology Based on (RII) Results (N = 250).

Table 11 shows descriptive statistics and the value of (RII) of four indicators of the total effect and acceptance of nanotechnology in construction projects. The findings indicate a rather positive view of the nanotechnology perceptions among the respondents (N = 250), and there is a different level of agreement on the benefits and strategic value of nanotechnology. The top-ranked one being, the adoption of nanotechnology aligns with the trends of innovation and development (RII = 80), meaning that there is a high level of awareness that nanotechnology is in line with global trends of technological innovation and highly developed materials. This corresponds to the previous research showing that nanotechnology is one of the major ways to transform

construction practices and foster an innovative environment in a project [49].The second one indicates the presence of added value; Nanotechnology has offered benefits over traditional methods (RII =72); it indicates that nanotechnology respondents are of the opinion that nanotechnology can add value to a performance that the traditional techniques cannot. This observation can be correlated with the studies that indicate that the nanomaterials enhance the strength, durability, and efficiency of operation, thus producing the tangible added value [50].The third statement, “Using nanotechnology has assisted in enhancing stakeholder satisfaction (RII = 70), brings out the role played by the technology in improving outcomes in quality, defects, and project results, which are known to increase stakeholder satisfaction. Other sources ensure the existence of prior research suggesting that the implementation of innovative materials and smarter technologies is strongly associated with improved end-user satisfaction and the enhanced delivery of the project.The least-rated one, which is Nanotechnology, has contributed to the improvement of competitive advantage (RII = 68) yet shows a more positive picture, though with a little lower agreement. Although the respondents appreciate the fact that nanotechnology has the potential of enhancing competitiveness, the comparatively lower (RII) indicates that its strategic value may not be wholly achieved or even current in practice. The same results are indicated by the literature, stating that competitive advantage is only created after a prolonged incorporation of technology and organizational preparedness [51].Generally, the findings reveal that nanotechnology is very acceptable and perceived to be useful, particularly in the aspects of innovation alignment and added value. Strategic advantages like competitive positioning, however, might take a longer time and industry adoption.

Table 11. The overall impact and acceptance: Descriptive Statistics, Frequencies, and (RII) Results (N = 250).

| Rank | Item   | Strongly Disagree (1) | Disagree (2) | Neutral (3) | Agree (4) | Strongly Agree (5) | Mean  | SD    | RII% |
|------|--|-----------------------|--------------|-------------|-----------|--------------------|-------|-------|------|
| 1    | The adoption of nanotechnology aligns with innovation and development trends               | 0                     | 24           | 0           | 179       | 47                 | 3.996 | 0.758 | 80   |
| 2    | The application of nanotechnology has provided added value compared to traditional methods | 0                     | 25           | 75          | 125       | 25                 | 3.600 | 0.802 | 72   |
| 3    | Using nanotechnology has helped increase stakeholder satisfaction                          | 27                    | 17           | 63          | 86        | 57                 | 3.516 | 1.223 | 70   |
| 4    | Using nanotechnology has contributed to enhancing competitive advantage                    | 22                    | 0            | 81          | 147       | 0                  | 3.412 | 0.879 | 68   |

Table 12. Quality Practices and Barriers: Descriptive Statistics, Frequencies, and (RII) Results (N = 250).

| Rank | Item  | Not influential at all (1) | Slightly influential (2) | Moderately influential (3) | Influential (4) | Very influential (5) | Mean  | SD    | RII% |
|------|---|----------------------------|--------------------------|----------------------------|-----------------|----------------------|-------|-------|------|
| 1    | Weak governmental support slows the adoption of nanotechnology                    | 21                         | 0                        | 49                         | 45              | 135                  | 4.092 | 1.220 | 82   |
| 2    | Difficulty in sourcing or the lack of local availability of nanomaterials         | 20                         | 0                        | 35                         | 92              | 103                  | 4.032 | 1.129 | 81   |
| 3    | Weakness or insufficiency of testing and laboratory examinations of nanomaterials | 15                         | 47                       | 54                         | 60              | 74                   | 3.524 | 1.258 | 70   |

|   |   |    |    |     |     |    |       |       |    |
|---|---|----|----|-----|-----|----|-------|-------|----|
| 4 | Limited access to certified testing bodies or accredited laboratories | 23 | 24 | 68  | 69  | 66 | 3.524 | 1.236 | 70 |
| 5 | The high initial cost of nanomaterials                                | 0  | 0  | 140 | 110 | 0  | 3.440 | 0.497 | 69 |
| 6 | Lack of specifications and standards                                  | 48 | 44 | 45  | 113 | 0  | 2.892 | 1.179 | 58 |
| 7 | Concerns related to occupational safety and health                    | 44 | 69 | 52  | 42  | 43 | 2.884 | 1.353 | 58 |

It can be seen in Table 12 that the application of nanotechnology is primarily limited by institutional, technical, and economic factors, with the weak governmental support being the most significant factor (RII = 82%), the inability to obtain nanomaterials locally coming next (RII = 81%), so policy commitment and supply-chain barriers are the primary issues. The obstacles associated with the testing capacity and the availability of certified labs were also quite high (RII = 70%), which was associated with the lack of proper technical infrastructure, though the high initial cost of nanomaterials was highly endorsed between the respondents, albeit slightly (RII = 69%). Conversely, specifications and standards are lacking, and occupational safety and health concerns were seen as influencing moderately (RII = 58%), which argues that regulatory and safety issues, though significant, are not as immediate impediments as governance, availability, and cost. This being the case, the findings emphasize the necessity to provide more policy support and better laboratory infrastructure and local supply systems so as to allow the adoption of nanotechnology [52].

**4.1 Multiple Regression Analysis**

To examine the impact of nanotechnology on project performance, a multiple linear regression analysis was conducted. Project performance was treated as the dependent variable, while five dimensions associated with nanotechnology adoption were considered independent variables: time performance, cost performance, quality and durability, safety and health, and sustainability.

The regression model is specified as follows [53]:

$$Y = \beta_0 + \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_4X_4 + \beta_5X_5 + \varepsilon \dots \dots (1)$$

Where:

$Y$  (T) denotes project performance.

$X_1-X_5$  represent the independent variables.

$\beta_0$  is the intercept.

$\varepsilon$  is the error term.

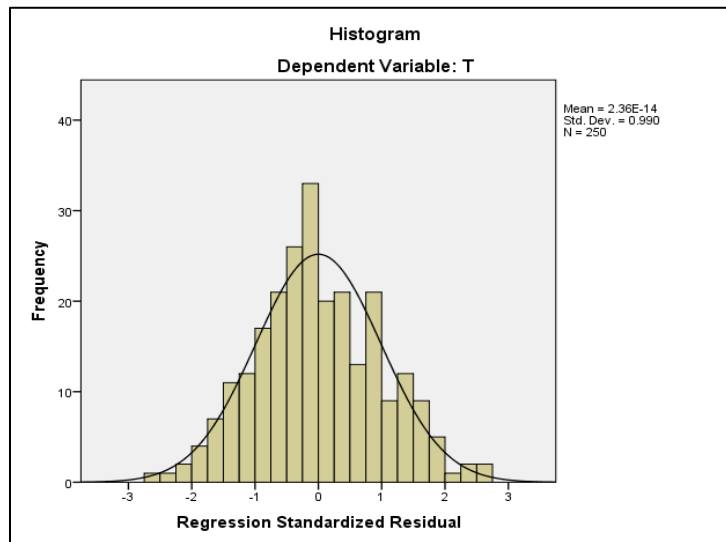


Figure 6. Histogram of Regression Residuals.

The histogram of the standardized residuals of the regression model is plotted in Figure 6. It is distributed more or less in a normal bell-shaped pattern whereby the residual values are centered at zero (Mean = 0) and the standard deviation is near to unity (Std. Dev. = 0.990). It means that the regression assumptions of the normality of the residuals are fulfilled sufficiently. The fact that the skewness and kurtosis are not significant implies that the mode is not biased systematically or abnormally distributed. Therefore, the regression estimates and statistical tests together with the high coefficient of determination are valid and confirm that the explanatory power of the model is the representation of a real relationship and not overfitting.

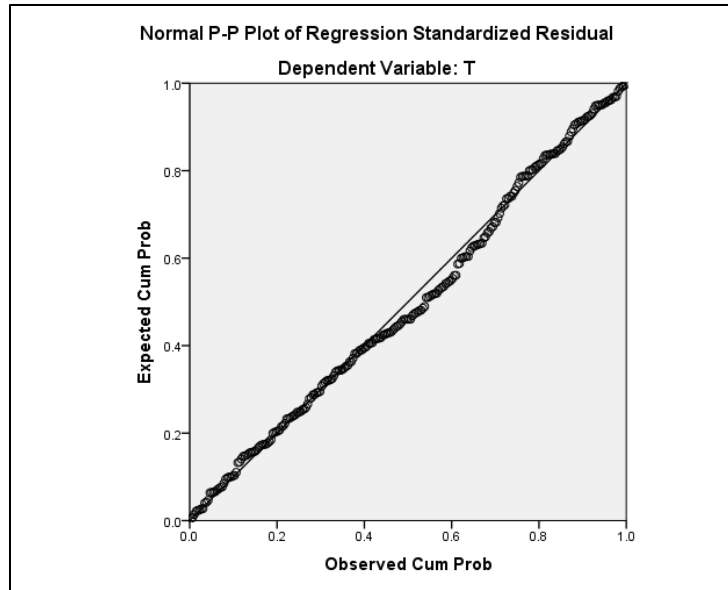


Figure 7. Normal P–P Plot Interpretation.

The Figure above (7) is the P-P plot of standardized residuals of the dependent variable regression. The observed cumulative probabilities are similar to the expected cumulative probabilities on the line of reference i.e. along the diagonal thus showing that the residuals are distributed normally. There are no systematic deviations, curvature or clustering in the plot, which validates the assumption of normality of regression residues. The outcome asserted the soundness of the statistical tests used in the regression analysis and the fact that the high explanatory power of the model is not the outcome of abnormal error distribution and overfitting.

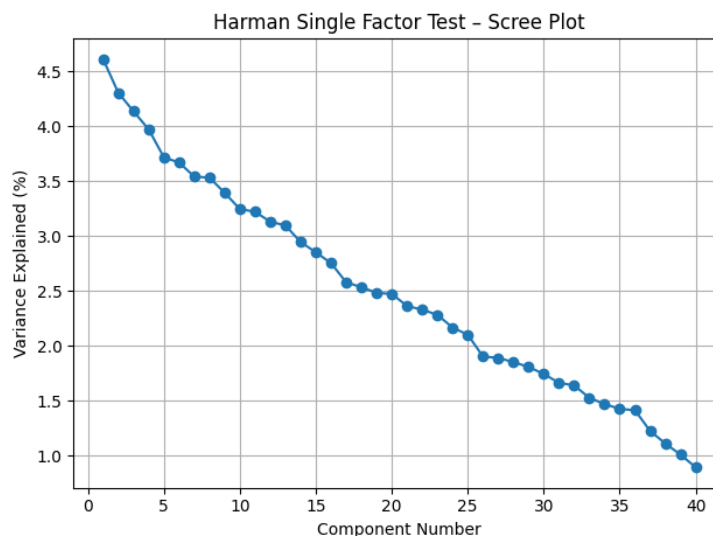


Figure 8. Harman Single Factor Test.

In order to determine the possible presence of common method variance (CMV), the single-factor test of Harman was done through unrotated principal component analysis of all the items in the questionnaire. The Figure above (8) findings revealed that the first factor only explained a percentage of 4.61 of the total variances which is considerably lower than the recommended percentage of 50. This means that the issue of common method variance is not severe in this research and the chances of biasness because of common method of measurement is low.

Table 12. Model Summary.

| Model | R                 | R Square | Adjusted R Square | Std. Error of the Estimate | Change Statistics |          |     |     |               |
|-------|-------------------|----------|-------------------|----------------------------|-------------------|----------|-----|-----|---------------|
|       |                   |          |                   |                            | R Square Change   | F Change | df1 | df2 | Sig. F Change |
| 1     | .942 <sup>a</sup> | .886     | .885              | .05200                     | .886              | 382.517  | 5   | 244 | .000          |

a. Predictors: (Constant), x1, x2, x3, x4, x5

Table 13. ANOVA<sup>a</sup>

| Model        | Sum of Squares | df  | Mean Square | F       | Sig.              |
|--------------|----------------|-----|-------------|---------|-------------------|
| 1 Regression | 5.172          | 5   | 1.034       | 382.517 | .000 <sup>b</sup> |
| Residual     | .660           | 244 | .003        |         |                   |
| Total        | 5.832          | 249 |             |         |                   |

a. Dependent Variable: Y (T)  
 b. Predictors: (Constant), x1, x2, x3, x4, x5

Table 12 shows that the regression results are highly satisfactory. The coefficient of determination ( $R^2 = 0.887$ ) implies that the independent variables in the model do explain about 88.6 percent of the variance in project performance. The value of Adjusted  $R^2$  (0.885) almost equals the  $R^2$  value, and the difference is only 0.001 which is a very important measure of model strength. Adjusted  $R^2$  is a measure of the number of predictors in the model and it punishes the extraneous variables which do not add significant explanatory power. The impact of the difference between  $R^2$  and Adjusted  $R^2$  is negligible, which attest that the model is not overfitted and that each predictor is providing valuable and independent information in explaining project performance.

The F-statistic ( $F = 382.517, p < 0.001$ ) shows that the regression model overall is statistically significant, which means that the independent variables forming a complex affect the project performance in a significant manner. Table 13 reveals the outcome of ANOVA test of the multiple regression model which investigated the effects of nanotechnology dimensions on performance of project. The outcomes show that regression model is significant ( $F = 382.517, p < 0.001$ ). This proves that the combination of independent variables, which include time performance, cost performance, quality and durability, safety and health, and sustainability, explain a large percentage of the changes in the performance of the projects. The value of regression sum of squares (5.172) is much larger than the value of residual sum of squares (0.660) and this shows that the model accounts most of the variation in the dependent variable. The residual low mean square error (0.003) also shows that there is a good fit of the model and the amount of unexplained variance is very small. Altogether, the results of ANOVA confirm the sufficiency of the regression model and its strength, which confirms the fact that the impact of the predictors is statistically significant and has an overall effect on project performance.

Table 14. Presents the estimated regression coefficients, corresponding t-values, and significance levels.

| Variable                       | Standardized $\beta$ | t-value | p-value | Tolerance | VIF   | Interpretation              | Impact Size Interpretation |
|--------------------------------|----------------------|---------|---------|-----------|-------|-----------------------------|----------------------------|
| (Constant)                     | 0.305                | -       | -       | -         | -     | -                           | -                          |
| Time Performance ( $X_1$ )     | 0.218                | 17.63   | < 0.001 | 0.962     | 1.039 | Significant positive effect | Moderate to strong Impact  |
| Cost Performance ( $X_2$ )     | 0.240                | 21.91   | < 0.001 | 0.955     | 1.047 | Significant positive effect | Strong Impact              |
| Quality & Durability ( $X_3$ ) | 0.215                | 15.57   | < 0.001 | 0.949     | 1.054 | Significant positive effect | Moderate to strong Impact  |
| Safety & Health ( $X_4$ )      | 0.100                | 11.17   | < 0.001 | 0.967     | 1.034 | Significant positive effect | Small to moderate Impact   |
| Sustainability ( $X_5$ )       | 0.150                | 19.55   | < 0.001 | 0.963     | 1.039 | Significant positive effect | Moderate Impact            |

$$Y = 0.31 + 0.218X_1 + 0.240X_2 + 0.215X_3 + 0.100X_4 + 0.150X_5 \dots\dots(2)$$

Table 14 shows that the standardized regression coefficients ( $\beta$ ) were employed to assess the relative magnitude of the impact of each nanotechnology-related dimension on project performance, as standardized coefficients allow meaningful comparison of effect sizes among predictors measured on different scales [53,54].

According to widely accepted benchmarks, ( $\beta$ ) values close to 0.10 indicate a small effect, values around 0.20 indicate a moderate effect, and higher values reflect a stronger influence. The results indicate that cost performance ( $\beta = 0.240$ ) has the largest influence on project performance among other factors and this highlights the importance of nanotechnology in contributing to cost performance by using less material, lifecycle performance and rework is minimized. Time performance ( $\beta = 0.218$ ) and quality and durability ( $\beta = 0.215$ ) show moderate to strong effects i.e., nanotechnology plays a significant role in the acceleration of the delivery of the project and better structural response through the improvement of the construction process and material characteristics. Sustainability exhibits a moderating effect ( $\beta = 0.150$ ), which implies that nanotechnology-mediated practices toward sustainability (resource efficiency and reduction of environmental impact) are rather significant but with secondary effects on the overall project success. Although statistically significant, safety and health have a relatively smaller impact size ( $\beta = 0.100$ ), indicating that nanotechnology has a small to moderate impact on project performance, meaning that although it enhances the safety conditions and minimizes the health risk, the effect is less direct as compared to economic and operational factors. In general, the findings point to the idea that the adoption of nanotechnology has a favorable impact on the performance of projects when evaluated in all the dimensions discussed, although its positive outcomes occur most in terms of cost, time, and quality outcomes. Multicollinearity diagnostics confirm the robustness of the model, as all tolerance values exceed 0.94 and Variance Inflation Factor (VIF) values remain close to 1.0, indicating the absence of multicollinearity concerns. These findings confirm that each predictor contributes uniquely to explaining variations in project performance and that the regression estimates are stable and reliable.

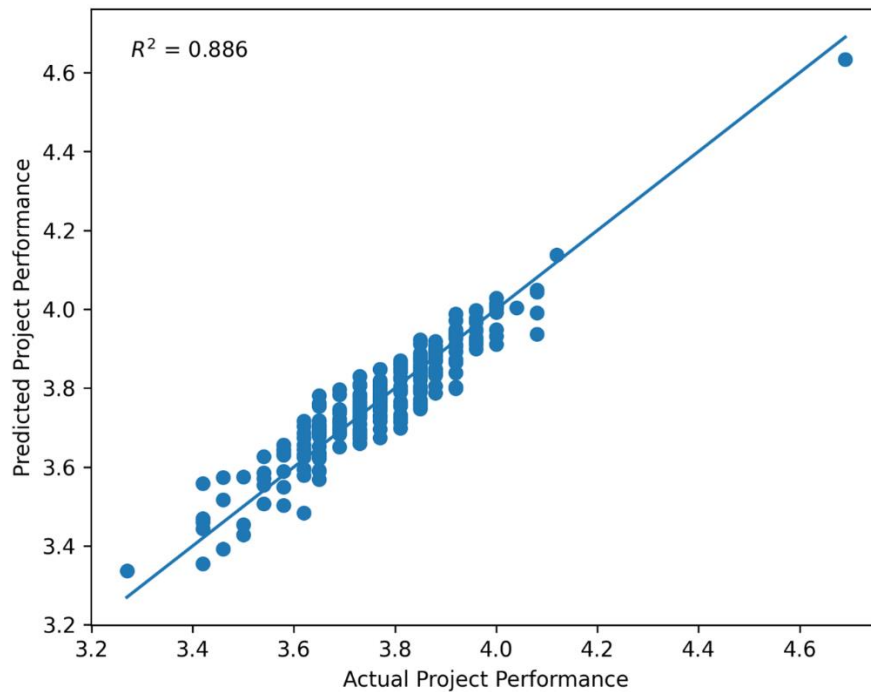


Figure 9. Comparison of Actual and Predicted Project Performance.

Figure 9 shows the correlation of the actual and predicted values of the project performance of the multiple regression model. The scatter points are highly concentrated around the reference line ( $y = x$ ), which means that it is high agreement on the values observed and predicted. The high explanatory power and predictive accuracy of the model is proved by the coefficient of determination ( $R^2 = 0.886$ ), which shows that the model can explain almost 88.6 percent of the variance in project performance. The fact that the spread of the points around the regression line is not high indicates that the prediction error is negligible and the regression model is considered to be robust and reliable in the process of predicting project performance based on nanotechnology dimensions.

Table 15. Relative Importance Index (RII) and Standardized Regression Coefficients ( $\beta$ ) for Project Performance Dimensions.

| Dimension            | RII   | $\beta$ |
|----------------------|-------|---------|
| Cost Performance     | 0.757 | 0.240   |
| Time Performance     | 0.742 | 0.218   |
| Quality & Durability | 0.731 | 0.215   |
| Sustainability       | 0.734 | 0.150   |
| Safety & Health      | 0.740 | 0.100   |

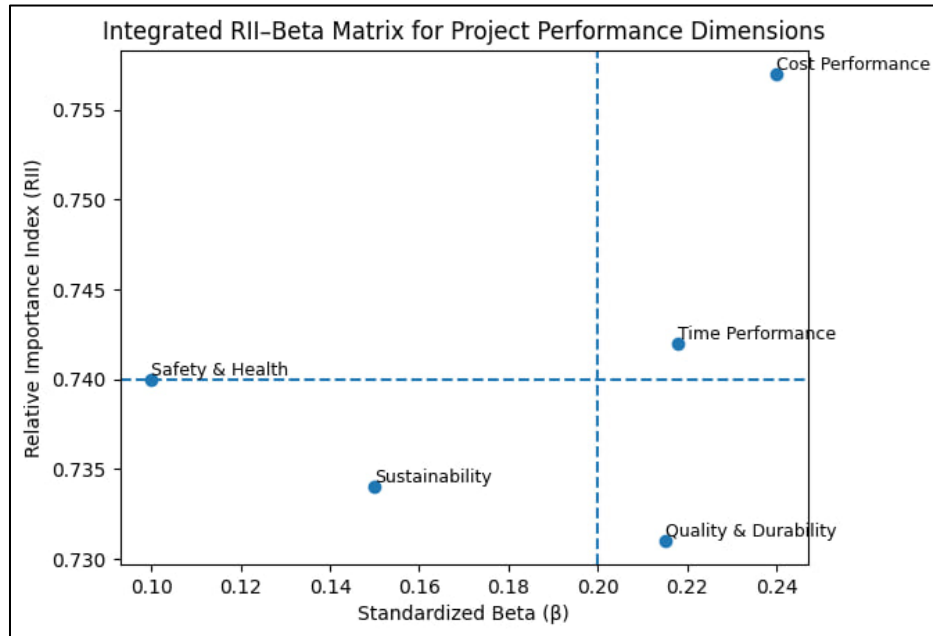


Figure 10. Integrated RII -Beta Matrix Illustrating the Relationship between Perceived Importance and Statistical Impact of project performance dimensions.

The concurrent interpretation of the (RII) values and ( $\beta$ ), as presented in **Table 15** and illustrated in Figure 10, provides a comprehensive understanding of how nanotechnology applications influence the performance of civil engineering projects by distinguishing between perceived importance and actual statistical impact. While (RII) represents a perception-based ranking of performance dimensions as evaluated by industry practitioners, standardized regression coefficients ( $\beta$ ) quantify the relative explanatory power of each dimension within the regression model while controlling for the effects of other variables [54,55]. The integration of these two measures has been widely recognized in construction management research as a robust analytical approach, as it mitigates the limitations associated with relying solely on perception-based rankings and enables a more rigorous interpretation of performance drivers [56,57]. These findings show that cost performance is the most important dimension, which has the greatest perceived importance (RII = 0.757) and has the greatest statistical effect on the overall project performance ( $\beta = 0.240$ ). The fact that it is situated in the high RII -high  $\beta$  quadrants of the matrix, proves that the advantages associated with nanotechnology cost-related, i.e., reduction of waste, minimization of rework and reduced life-cycle cost efficiency, are the main driver of the measurable project performance. This result corresponds with the previous studies that have stressed that economic efficiency is the most compelling factor behind the use of advanced technologies in construction projects, especially in developing and resource-restricted situations [57,35]. Performance in time also exhibits high convergence of perception and empirical impact with the value of (RII=0.742) being large and standardized coefficient ( $\beta = 0.218$ ) is high. The fact that it fits the high RII -high  $\beta$  region of the matrix with the cost performance implies that speeding up of the schedule, shortening of delays, and enhancing efficiency in its construction are major benefits of the nanotechnology in terms of operations. This correspondence indicates that the perception of practitioners is well-representative of the objective time-based performance benefits linked with nano-enhanced materials and processes, which aligns with the previous results on

the productivity gains in construction brought about by innovation [58]. Conversely, quality and durability have a perceived importance that is comparatively lower ( $RII = 0.731$ ) with a high level of statistical impact ( $\beta = 0.215$ ). The matrix has graphically indicated this difference by placing quality and longevity in a high  $\beta$  with a relatively low level of RII. The trend here indicates that the real effects of nanotechnology on the material performance, structural integrity and long-term durability might be underestimated by the practitioners. The numerous experimental studies have shown that nano-modified cementitious materials can greatly increase the mechanical strength and deterioration resistance, thus producing a high impact on the project performance despite the fact that these advantages may not be apparent at the time of construction [59]. Sustainability holds an intermediate rank in the table ( $RII = 0.734$ ;  $0.150$ ;  $0 = 0.150$ ) and the matrix, which makes it a secondary yet equal contribution to the overall project performance. This positioning suggests that the results of sustainability, i. e. a lower environmental impact, resource efficiency, and a longer service life, are significant contributors to the project success, but those are achieved rather in the long run than during the short-term benefits of the operation. This finding is in line with the literature on sustainability, which highlights the importance of life-cycle value and long-term resilience, instead of short-term indicators on performance [43]. Lastly, safety and health exhibit relatively high perceived importance ( $RII = 0.740$ ) but the lowest standardized regression coefficient ( $\beta = 0.100$ ). This gap, depicted in the table and the high-RII-low-B quadrant of the matrix, implies that the advantages of nanotechnology in terms of safety and health are well-known by the practitioners but have a more indirect impact on the performance of the entire project. Safety and health improvements are often enabling conditions that reduce risks, eliminate failures, and facilitate regulatory compliance, and not drivers of cost or time performance [59]. In general, the sequential analysis of the table and the matrix affirms that nanotechnology application improves the performance of the civil engineering project mainly in cost efficiency, time saved, and higher quality of materials, whereas the fact of safety and sustainability is relevant to the long-term robustness and resilience. To that end, the integrated RII-Beta approach offers a sophisticated and analytically sound insight into the effects of performance that would not have been possible to acquire using descriptive or regression analysis.

## 5. CONCLUSION

This study comprehensively examined the impact of nanotechnology applications on the performance of civil engineering projects in Iraq using empirical field data collected from 250 professionals. The findings from descriptive statistics and (RII) analysis revealed that nanotechnology is perceived to have a positive influence across all major performance dimensions, particularly in cost efficiency, time reduction, and quality and durability enhancement. Reliability analysis confirmed strong internal consistency for all questionnaire constructs, with Cronbach's alpha values ranging from 0.82 to 0.88, ensuring the robustness of the measurement instrument. The multiple regression analysis further validated these findings, demonstrating a highly significant and well-fitted model ( $R^2 = 0.886$ ,  $F = 382.517$ ,  $p < 0.001$ ), indicating that nanotechnology dimensions explain approximately 88.6% of the variance in overall project performance. Among the predictors, cost performance exhibited the strongest impact, followed by time performance and quality and durability, confirming that nanotechnology primarily enhances economic efficiency, accelerates project execution, and improves material performance and structural longevity. Safety, health, and sustainability, although showing relatively smaller effect sizes, remained statistically significant, highlighting the supportive role of nanotechnology in improving workplace safety, reducing environmental impacts, and promoting long-term sustainability. The integrated RII-Beta matrix confirms that project performance dimensions exhibiting both high perceived importance and strong statistical impact—particularly cost and time performance—represent the core drivers of nanotechnology effectiveness in civil engineering projects, while quality, sustainability, and safety function as enabling dimensions that enhance long-term resilience and overall project value. Despite the identification of implementation barriers—such as weak governmental support, limited local availability of nanomaterials, and high initial costs—the overall results clearly demonstrate that nanotechnology represents a viable and effective solution for overcoming chronic challenges in Iraqi civil engineering projects. Consequently, the study concludes that wider adoption of nanotechnology, supported by improved policies, technical infrastructure, and institutional capacity building, can substantially enhance project performance and contribute to more efficient, durable, safe, and sustainable construction practices in Iraq. This study relies on self-reported perceptions collected through a questionnaire, which may introduce response bias. In addition, the use of purposive sampling limits the generalizability of the findings. Future research may incorporate objective performance indicators and experimental data to validate the perceived impacts of nanotechnology.

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