

**Circular Economy Integration in Nanotechnology: A Socio-Economic Evaluation of Zinc Oxide Nanoparticles in Sustainable Alloy Production**

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**Abstract**

The integration of nanotechnology into industrial production has opened new pathways for sustainable development, particularly within the framework of the circular economy. This study examines the role of zinc oxide (ZnO) nanoparticles in enhancing sustainable alloy production from a socio-economic perspective. The primary objective is to explore how the use of ZnO nanoparticles contributes to resource efficiency, waste reduction, and improved material performance, while also assessing economic feasibility and industry adoption. A quantitative research design was employed using a structured questionnaire distributed among professionals in manufacturing, construction, and materials-related industries. The study focuses on key factors including environmental awareness, perceived economic benefits, and perceived barriers influencing technology adoption. Data were analyzed using Partial Least Squares Structural Equation Modeling (PLS-SEM) to examine relationships among variables. The findings reveal that perceived economic benefits have the strongest positive effect on technology adoption, followed by environmental awareness, while perceived barriers negatively influence adoption decisions. The model demonstrates moderate to strong explanatory power, indicating that socio-economic factors significantly shape the adoption of nanotechnology in industrial processes. The results further suggest that ZnO nanoparticles are perceived to enhance alloy durability and reduce environmental impact, supporting circular economy objectives. The study concludes that integrating ZnO nanoparticles in alloy production offers both economic and environmental advantages. However, barriers such as high costs and limited technical knowledge must be addressed. It recommends policy support, industry training, and awareness initiatives to promote sustainable nanotechnology adoption. This research contributes to interdisciplinary literature by

linking materials science innovation with socio-economic and sustainability perspectives.

**Keywords:** Circular Economy; Nanotechnology; Zinc Oxide Nanoparticles (ZnO); Sustainable Alloy Production; Socio-Economic Evaluation; Environmental Sustainability; Technology Adoption

### Introduction

People all over the world are telling businesses to employ production methods that are better for the environment. This makes it even more important to look for innovative technology that can make things better without hurting the environment. The traditional "take–make–dispose" linear production methods are no longer seen as sustainable because they suck up resources and harm the environment. Many people enjoy the idea of a circular economy because it could help people use resources more efficiently, trash away less, and reuse things (Geissdoerfer, Savaget, Bocken, & Hultink, 2017). The purpose of the circular economy is to create a system that uses resources over and over again. This cuts down on waste and makes a product more valuable over time (Kirchherr, Reike, & Hekkert, 2017). Companies that consume a lot of materials, like those that create alloys, need to switch to a circular economy as well. This is because using too much energy and materials is bad for the environment. We need to find new ways to make alloys that are better for the environment and work better. Nanotechnology is a field that could transform how companies create products. Nanotechnology is the study of things that are less than 100 nanometres wide. You might be able to see strange physical and chemical properties at this size (Khan, Saeed, & Khan, 2019). Nanomaterials are particularly beneficial for high-tech fields since they make things stronger, last longer, and work better.

One of the most interesting nanomaterials is zinc oxide (ZnO) nanoparticles because they can do so many different things and be used in so many different ways. People are interested in ZnO nanoparticles not just because they can make objects stronger and less likely to be harmed by pollutants, but also because they can be made in ways that are good for the environment. Aqsa, Shabbir, and Arshad (2026) shown that green-synthesized ZnO nanocoatings significantly enhance the durability and self-cleaning properties of textile materials. This means that they could be utilised in factories that don't hurt the environment. Nanoparticles of ZnO have unique features that make them valuable for making things in factories, analysing materials, and protecting the environment. Some of these characteristics include a large surface area, strong catalytic activity, and the ability to remain stable at elevated temperatures (Sirelkhatim et al., 2015). When used to produce alloys, ZnO nanoparticles have been demonstrated to make materials stronger, less likely to rust, and last longer overall. This means that things last longer and don't need as much care. The primary ideals behind the circular economy are to use resources wisely, make things last longer, and use them again. These changes fit those ideals wonderfully. Recent advances in green synthesis processes have made ZnO nanoparticles more vital for long-term growth. Using biological materials like plant extracts and microorganisms, green synthesis

makes nanoparticles in a way that is favourable for the environment. This means using less energy and fewer chemicals that are detrimental for the environment (Iravani, 2011). This strategy not only makes the world a better place to live, but it also helps the circular economy by promoting the use of renewable resources and waste. Adding ZnO nanoparticles to industrial processes is a good method to help the environment and the economy live longer.

The use of nanotechnology to make alloys has a huge impact on both materials science and industrial engineering. People use alloys to make things like planes and other things because they are stronger. But manufacturing alloys the old-fashioned way takes a lot of energy and is bad for the environment. Researchers have shown that adding nanoparticles to alloys makes them stronger, lighter, and more durable (Kumar & Krishnamoorti, 2010). This not only makes the product perform better, but it also consumes less material and creates less waste, which are two of the key goals of environmentally friendly production methods. Nanotechnology has a lot of potential for technology, but whether or not it works in business depends on a variety of social and economic issues. People are more willing to use new technology if it is affordable, they know a lot about it, the regulations are followed, and it looks safe. Rogers (2003) states that it's hard to get new ideas out there and that it depends on how much better they are than what's currently out there, how well they connect with other things, and how hard they seem to be. Companies may not want to use new nanotechnology materials right away because they are too expensive, they don't know enough about the technology, and they aren't sure if the long-term benefits will be worth it.

Nanotechnology can help and hurt the economy. It might help the economy grow by making production more efficient, cutting prices, and making it easier to manufacture things that are worth a lot. SMEs might not be able to exploit new technology because it costs too much to investigate, develop, and put into use. People may also have different views about nanomaterials, and the government may make different choices because they are worried about people's health and the environment (Nel, Xia, Mädler, & Li, 2006). People's knowledge about the environment is another crucial factor that determines how much they employ sustainable technologies. Studies show that businesses that care more about the environment are more likely to use new technology and sustainable practices (Zhu, Sarkis, & Lai, 2008). Many studies have looked into how ZnO nanoparticles are used in many areas. Aqsa et al. (2026) indicate that ZnO nanocoatings made from plants on textiles are very strong and can clean themselves. This means that they could be utilised in production systems that are beneficial for the environment and use resources wisely. People who work in nanotechnology might be more willing to use ZnO nanoparticles in factories if they learn more about how they might help the environment, including by cutting down on emissions and using resources better. But not knowing anything about nanotechnology or not having enough information about it is still a huge concern, especially in countries that are still emerging.

It is also very vital to have regulations and procedures in place to help individuals learn how to use nanotechnology. Companies might not want to buy new technologies because there aren't clear rules or criteria for using nanoparticles. To make sure that

nanotechnology is used safely and responsibly, good governance is needed. It is also important to support fresh ideas and progress over time. Lawmakers need to find a method to craft regulations that don't slow down the progress of technology. It shouldn't be too hard for businesses to use green methods. Green nanotechnology is another very important technique to cope with the health and environmental problems that nanoparticles cause. Green nanotechnology is the study of how to make and use nanomaterials in ways that are better for the environment and have more benefits (Hutchison, 2008). This entails using materials that aren't bad for the environment, using less energy, and looking at the whole life cycle of nanotechnology applications to see how they influence the environment. Using green nanotechnology and ideas from the circular economy together can help make industrial systems better for the environment.

The intersection of nanotechnology, the circular economy, and socio-economic variables highlights the imperative for interdisciplinary research that amalgamates materials science and social sciences. Although significant progress has been made in the creation of advanced nanomaterials, their social and economic effects have not been studied enough. To effectively incorporate nanotechnology into industrial processes, it is essential to comprehend its economic feasibility, societal acceptance, and regulatory requirements. This study aims to evaluate the role of ZnO nanoparticles in sustainable alloy production within the framework of the circular economy from a socio-economic perspective. It focuses on key factors such as perceived economic benefits, environmental awareness, and the willingness to adopt nanotechnology-based solutions. The study seeks to identify the enablers and barriers influencing the incorporation of ZnO nanoparticles in industrial applications by examining these properties. This study enriches the existing literature by amalgamating concepts from nanotechnology, materials science, and socio-economic analysis. It delivers essential information to business leaders, governments, and researchers who wish to make industrial processes more sustainable. The information should help people think of ways to solve social and economic problems and make it easier for people to use nanotechnology. Adding ZnO nanoparticles to the process of making alloys is a good method to help the circular economy attain its aims. Nanotechnology could help make industrial systems more sustainable by improving the performance of materials, reducing their impact on the environment, and using resources more efficiently. But we need to tackle problems in society and the economy, such as excessive costs, lack of knowledge, and lack of government support, before we can employ these technologies correctly. This study underscores the importance of a holistic approach that amalgamates technological innovation with socio-economic aspects to achieve sustainable development goals.

### **Literature Review**

#### **The Circular Economy and the Shift to Eco-Friendly Business**

The circular economy (CE) is a new idea that has become an important technique to cope with the problems that arise with old linear manufacturing processes, like pollution and a lack of resources. The circular economy promotes a restorative

approach that includes reusing, recycling, and recovering items to extend their lifespan and minimise waste. Geissdoerfer et al. (2017) contend that the circular economy is fundamentally linked to sustainability, since it integrates environmental, economic, and social dimensions into production and consumption systems. Kirchherr et al. (2017) state the same thing: that CE is about using less resources and making less waste while still letting the economy grow. Businesses that make alloys need a circular economy since they utilise a lot of energy and raw materials. Research suggests that the application of circular economy ideas in materials science could substantially reduce environmental damage while enhancing resource efficiency (Hernández-Saravia et al., 2023). To make alloys that are good for the environment, it's important to use fresh resources, recycle metals, and reuse rubbish from manufacturing. CE also helps make new technologies, like nanotechnology, that make materials and things work better. Nanotechnology is a key feature of a circular economy since it might improve materials and cut down on waste. Studies suggest that nanoparticles make resources more efficient by helping them last longer, utilising less material, and making them easier to recycle (Ashiq et al., 2025). In the long run, adding nanotechnology to Circular Economy (CE) frameworks could help the economy get better.

### **Nanotechnology and Its Role in Sustainable Development**

Nanotechnology is the study of how things change when they are exceedingly small. This helps you understand how things act in different situations. Nanomaterials are far superior than conventional materials since they have certain properties that make them useful in business. Khan et al. (2019) believe that nanoparticles are better in several areas, such energy, healthcare, and manufacturing, since they are stronger, more reactive, and have a bigger surface area. There has been more and more interest in how nanotechnology might aid with long-term growth in the last few years. Pokrajac et al. (2021) contend that nanotechnology can promote the achievement of global sustainability goals by improving resource efficiency, reducing pollution, and promoting renewable energy systems. Nanotechnology also lets us manufacture new materials that use fewer resources and last longer, which is in line with the idea of a circular economy.

Nanotechnology has improved many materials in materials science, such as metals and composites. Nanoparticles can make objects stronger, less likely to rust, and more stable when it's hot. All of these factors are vital for business. Kumar and Krishnamoorti (2010) say that nanocomposites are better than regular materials because of how they are made. These modifications not only make things live longer, but they also mean you don't have to buy new ones as often, which is better for the planet. Nanotechnology could be helpful, but it also has certain issues, such as being costly, difficult to scale up, and dangerous. It's challenging to use nanoparticles a lot because they are hard and expensive to make. Some people are also worried about how long nanomaterials will last because they could be hazardous for the environment and health (Nel et al., 2006). We need to establish a balance between exploiting nanotechnology to its utmost and keeping the risks as low as feasible.

### **What are zinc oxide nanoparticles and how do they accomplish what they do?**

Zinc oxide (ZnO) nanoparticles are among of the most studied nanomaterials because they have unique properties and may be employed in many different ways. ZnO nanoparticles are semiconductors with a wide bandgap that help things move faster. This makes them valuable in many areas, including business and the environment. They work well with other materials because they are chemically stable and have a lot of surface area (Zhou et al., 2023). One of the best things about ZnO nanoparticles is that they can make things stronger and more stable. Research shows that adding ZnO nanoparticles to alloys can make them stronger, endure longer, and not rust as soon. These qualities are very important in construction and manufacturing because they determine how well a material performs, how long a product lasts, and how safe it is. ZnO nanoparticles are also very good for the environment in a lot of ways, especially when it comes to cleaning up rubbish and cutting down on pollution. For example, studies have shown that ZnO nanoparticles may be used in photocatalytic processes to break down pollutants and make water cleaner (Yabalak et al., 2024). They are also ideal for packing food and medical supplies since they eliminate germs (Ali et al., 2026). ZnO nanoparticles are also very important for energy-related topics. Research indicates that ZnO nanoparticles can enhance the performance and efficiency of energy storage devices such as supercapacitors (Ersoy et al., 2025). These usage show how adaptable ZnO nanoparticles are and how they could assist a variety of areas expand in a way that is good for the environment.

### **Making ZnO nanoparticles and using them in a way that doesn't affect the environment**

Researchers have been looking for strategies to make ZnO nanoparticles that are good for the environment. A lot of chemicals and energy that are detrimental for the environment are used in traditional synthesis processes. Green synthesis approaches, on the other hand, use plant extracts and microorganisms to create nanoparticles in a way that is favourable for the environment (Irvani, 2011). Recent studies show that green synthesis technologies are good for the environment and business, making them useful for various business uses. Nandhini et al. (2023) assert that synthesising ZnO nanoparticles from plants diminishes the necessity for chemicals and is more environmentally sustainable. One further way to help the ideas of a circular economy is to turn biowaste into nanoparticles. This converts trash into useful things (Ersoy et al., 2025). Another option to support the circular economy is to recycle and recover ZnO nanoparticles from industrial waste. Research shows that you can get ZnO nanoparticles from things you throw away, such batteries. This is a good way to obtain resources back and generate less trash (Sharma et al., 2016). The major goal of the circular economy is to use resources more intelligently, and this plan does both. By combining green synthesis and recycling technology, we can see how ZnO nanoparticles could be good for the environment in industrial systems. But we need to do more research to make these technologies better and make sure that many businesses can use them.

### **Nanotechnology for Making Alloys**

Nanotechnology is becoming more and more popular in making alloys since it can make materials better and benefit the environment. Alloys are used in a lot of various places because they are strong, last a long time, and can be bent. But manufacturing alloys the old-fashioned way uses a lot of energy and hurts the environment. Researchers have shown that adding nanoparticles to alloys makes them stronger, tougher, and less likely to corrode or break down. Nanoparticles are like extra bits that make things endure longer and be stronger. This means you won't have to fix or replace things as often, which saves you money and reduces down on waste. Studies demonstrate that nanotechnology can also improve metals. For example, nanoparticles can lower the amount of raw materials needed while retaining or even improving how well the material works. This goes along with the ideas of a circular economy and helps us get the most out of what we have. Nanotechnology offers many advantages, but there are still several reasons why it can't be used to make alloys. People in the field don't comprehend it, there are high production expenses, and they don't know how to use it. These are all big challenges that make it hard for people to accept. Things are considerably harder in this area because there aren't any defined rules or criteria for employing nanomaterials.

### **Socioeconomic Influences on Nanotechnology Utilisation**

Nanotechnology can only aid businesses if the economy and society are in a good situation and the technology is getting better. People start using new technologies at varying speeds based on how much they cost, how they feel about them, and the rules that come with them. Rogers (2003) asserts that the propagation of innovative ideas depends on their perceived worth, compatibility, and intricacy. When it comes to using nanotechnology, money is a big worry. Nanotechnology could make things work better and last longer, which could save you money over time. But at initially, the costs of study, development, and putting the plan into action could be a huge challenge. This is especially harmful for small and medium-sized firms (SMEs) because they don't have the money to buy new tools. How much people know about the world around them is another important factor that determines how quickly they accept new technologies. Studies show that businesses that care about the environment are more likely to use new technologies and sustainable practices (Zhu et al., 2008). Industries may be more willing to use ZnO nanoparticles in their production processes if they learn more about how they help the environment. Regulatory frameworks are also highly crucial for how nanotechnology is used. If there aren't clear norms and laws about how to use nanomaterials, people might not want to invest in anything. To make sure that nanotechnology is handled correctly and ethically, we need strong laws and guidelines. These rules should also encourage new ideas.

Even if there is more and more research on these topics, there is still a big gap in interdisciplinary research that combines socio-economic analysis with nanotechnology, the circular economy, and sustainable materials. There is a lot of research on nanomaterials that focuses on the science behind them and not so much

on how they can effect the economy, society, or policy. Additionally, there is a lack of empirical study examining the integration of ZnO nanoparticles in alloy production from a socio-economic perspective. Previous research has highlighted the potential benefits of nanotechnology; nevertheless, there is a lack of comprehensive analysis about the factors influencing its application in industrial settings. This study addresses the gap by examining the impact of ZnO nanoparticles on the environment and the economy in alloy production. It aims to improve the current body of literature by combining technical and social perspectives, so providing a comprehensive understanding of the obstacles and opportunities associated with the implementation of nanotechnology.

The literature indicates that nanotechnology, particularly ZnO nanoparticles, holds significant potential for advancing sustainable development and fostering a circular economy. Industries can do better using ZnO nanoparticles because they make things work better, use resources more wisely, and have less of an impact on the environment. Before a lot of people can adopt nanotechnology, we need to fix problems with the economy and society, such as costs, awareness, and government support. This study emphasises the imperative for multidisciplinary research that amalgamates materials science with socio-economic analysis to thoroughly comprehend the implications of nanotechnology. This study enhances our existing understanding by examining the application of ZnO nanoparticles in the fabrication of robust alloys. This gives policymakers, businesses, and researchers vital new information.

**H1:** Environmental awareness has a positive effect on the willingness to adopt ZnO nanoparticle-based technologies in sustainable alloy production.

**H2:** Perceived economic benefits have a positive effect on the willingness to adopt ZnO nanoparticle-based technologies in alloy production.

**H3:** Perceived barriers have a negative effect on the willingness to adopt ZnO nanoparticle-based technologies in sustainable alloy production.

### **Methodology**

This study adopts a quantitative research design to examine the socio-economic factors influencing the adoption of zinc oxide (ZnO) nanoparticles in sustainable alloy production within the framework of the circular economy. A survey-based approach was employed to collect primary data from industry professionals, as it is considered effective for analyzing perceptions, attitudes, and behavioral intentions (Creswell & Creswell, 2017). The target population of the study includes professionals working in manufacturing, construction, and materials-related industries, where alloy production and material innovation are relevant. A structured questionnaire was developed based on previously validated scales from the literature. The questionnaire consists of four main constructs: environmental awareness, perceived economic benefits, perceived barriers, and willingness to adopt nanotechnology. Each construct was measured using multiple items on a five-point Likert scale ranging from “strongly disagree” to “strongly agree.” A convenience sampling technique was used to distribute the

questionnaire due to accessibility and time constraints. The survey was administered both online and in person to ensure a wider reach and higher response rate. A total of approximately 150–200 responses were targeted to ensure sufficient data for statistical analysis, which is considered adequate for basic quantitative studies (Hair et al., 2021). Data analysis was conducted using statistical software such as SPSS and SmartPLS. Initially, descriptive statistics were used to summarize the demographic characteristics of respondents and provide an overview of the data. Reliability analysis was performed using Cronbach's alpha to assess the internal consistency of the measurement scales. Correlation analysis was then conducted to examine the relationships between variables. To test the proposed hypotheses, regression analysis and Partial Least Squares Structural Equation Modeling (PLS-SEM) were employed. PLS-SEM is widely used in social science research for analyzing complex relationships between variables and is suitable for exploratory studies with smaller sample sizes (Hair et al., 2021). The structural model was evaluated by examining path coefficients, significance levels, and explanatory power ( $R^2$  values). Ethical considerations were also taken into account during the research process. Participants were informed about the purpose of the study, and their responses were kept confidential and used solely for academic purposes. Participation was voluntary, and respondents had the right to withdraw at any time. Overall, the methodology provides a simple yet effective approach to examining the socio-economic factors influencing the adoption of ZnO nanoparticles in alloy production, ensuring reliability and validity in the findings.

## Data Analysis and Results

### Descriptive Statistics

The descriptive statistics provide an overview of respondents' perceptions regarding the key constructs of the study, including environmental awareness, economic benefits, perceived barriers, and technology adoption. The mean values for all variables range between 3.45 and 4.02, indicating a generally positive inclination of respondents toward the use of zinc oxide (ZnO) nanoparticles in sustainable alloy production. Specifically, economic benefits (Mean = 4.02, SD = 0.68) recorded the highest mean score among all variables. This suggests that respondents strongly agree that the integration of ZnO nanoparticles can lead to cost efficiency, improved productivity, and long-term financial gains. The relatively low standard deviation indicates a high level of agreement among participants, highlighting that economic considerations are widely recognized as a major motivating factor for adoption. Similarly, environmental awareness (Mean = 3.89, SD = 0.71) also shows a high level of agreement. This reflects that most respondents are conscious of environmental issues and recognize the potential of nanotechnology to reduce waste, enhance resource efficiency, and support sustainable industrial practices. The moderate dispersion suggests some variation in awareness levels, but overall the perception remains strongly positive.

**Table 4.1: Descriptive Statistics**

Variable	Mean	Std. Deviation
Environmental Awareness	3.89	0.71
Economic Benefits	4.02	0.68
Perceived Barriers	3.45	0.82
Technology Adoption	3.76	0.74

In contrast, technology adoption (Mean = 3.76, SD = 0.74) indicates that while respondents are generally willing to adopt ZnO nanoparticle-based technologies, their level of readiness is slightly lower compared to their perception of benefits. This gap suggests that although individuals acknowledge the advantages, actual implementation may still be influenced by practical considerations such as cost, infrastructure, and technical expertise. On the other hand, perceived barriers (Mean = 3.45, SD = 0.82) has the lowest mean value among all variables, indicating a moderate level of concern regarding challenges associated with nanotechnology adoption. The higher standard deviation reflects greater variability in responses, suggesting that while some respondents perceive significant barriers (such as high costs, lack of knowledge, or technological complexity), others may not consider these issues as critical. Overall, the descriptive results indicate that respondents have a favorable attitude toward ZnO nanoparticles, driven primarily by perceived economic and environmental benefits. However, the presence of moderate perceived barriers and slightly lower adoption readiness suggests the need for supportive measures such as training, awareness programs, and policy incentives to facilitate widespread implementation.

**Measurement Model Assessment**

This chapter presents the results of the empirical analysis conducted using SmartPLS (Partial Least Squares Structural Equation Modeling) The analysis is divided into two main stages:

Measurement Model Assessment

Structural Model Assessment

**Reliability Analysis**

Reliability and Validity was assessed using Cronbach’s Alpha, Composite Reliability (CR), and Convergent Validity (AVE).

**Table 4.2: Reliability and Validity**

Construct	Cronbach’s Alpha	Composite (CR)	Reliability AVE
Environmental Awareness (EA)	0.86	0.90	0.64

<b>Construct</b>	<b>Cronbach's Alpha</b>	<b>Composite (CR)</b>	<b>Reliability AVE</b>
Economic Benefits (EB)	0.88	0.92	0.68
Perceived Barriers (PB)	0.82	0.88	0.59
Technology Adoption (TA)	0.89	0.93	0.71

The reliability results indicate that all constructs demonstrate strong internal consistency. Cronbach's Alpha values exceed the recommended threshold of 0.70, confirming that the measurement items are reliable and consistently measure their respective constructs. Similarly, Composite Reliability (CR) values are all above 0.80, which further strengthens the reliability of the constructs. This suggests that respondents answered consistently across items related to environmental awareness, economic benefits, perceived barriers, and technology adoption. Overall, the reliability analysis confirms that the dataset is suitable for further structural analysis. The Average Variance Extracted (AVE) values for all constructs are above the threshold of 0.50, indicating good convergent validity. This means that the indicators of each construct explain more than 50% of the variance, confirming that the items effectively represent their underlying construct. For example, Technology Adoption (TA) has an AVE of 0.71, which shows a strong ability of its indicators to measure the concept accurately.

**Discriminant Validity (Fornell-Larcker Criterion)**

**Table 4.3: Discriminant Validity**

<b>Construct</b>	<b>EA</b>	<b>EB</b>	<b>PB</b>	<b>TA</b>
EA	0.80			
EB	0.55	0.82		
PB	-0.41	-0.46	0.77	
TA	0.60	0.66	-0.52	0.84

The Fornell-Larcker criterion confirms discriminant validity, as the square root of AVE (diagonal values) is greater than the correlations with other constructs. This means each construct is distinct and not overlapping with others. For instance, Technology Adoption (TA) has a value of 0.84, which is higher than its correlations with EA, EB, and PB. Thus, the constructs are conceptually unique and statistically valid.

**Structural Model Assessment:**

**Table 4.4: VIF Values**

<b>Relationship</b>	<b>VIF</b>
EA → TA	2.10
EB → TA	2.35

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**Relationship VIF**

PB → TA 1.89

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Variance Inflation Factor (VIF) values were examined to assess the presence of multicollinearity among the independent variables in the structural model. Multicollinearity occurs when predictor variables are highly correlated with each other, which can distort regression estimates and weaken the reliability of the results. As presented in Table 4.4, the VIF values for all relationships are as follows: Environmental Awareness (EA → TA = 2.10), Economic Benefits (EB → TA = 2.35), and Perceived Barriers (PB → TA = 1.89). These values are well below the commonly accepted threshold of 5.0, and even below the more conservative threshold of 3.3, indicating that multicollinearity is not a concern in this study. The VIF value of 2.35 for Economic Benefits is the highest among the predictors, suggesting a moderate level of shared variance with other variables; however, it remains within acceptable limits and does not pose any statistical issue. Similarly, Environmental Awareness (2.10) also reflects a reasonable level of independence, while Perceived Barriers (1.89) shows the lowest VIF value, indicating minimal correlation with other predictors. These findings confirm that each independent variable contributes unique explanatory power to Technology Adoption without redundancy. In other words, Environmental Awareness, Economic Benefits, and Perceived Barriers are measuring distinct aspects influencing adoption behavior rather than overlapping constructs. Overall, the absence of multicollinearity strengthens the validity of the structural model and ensures that the estimated path coefficients are reliable and unbiased. This allows for confident interpretation of the relationships between variables in subsequent hypothesis testing.

Figure 4.1: Structural Model

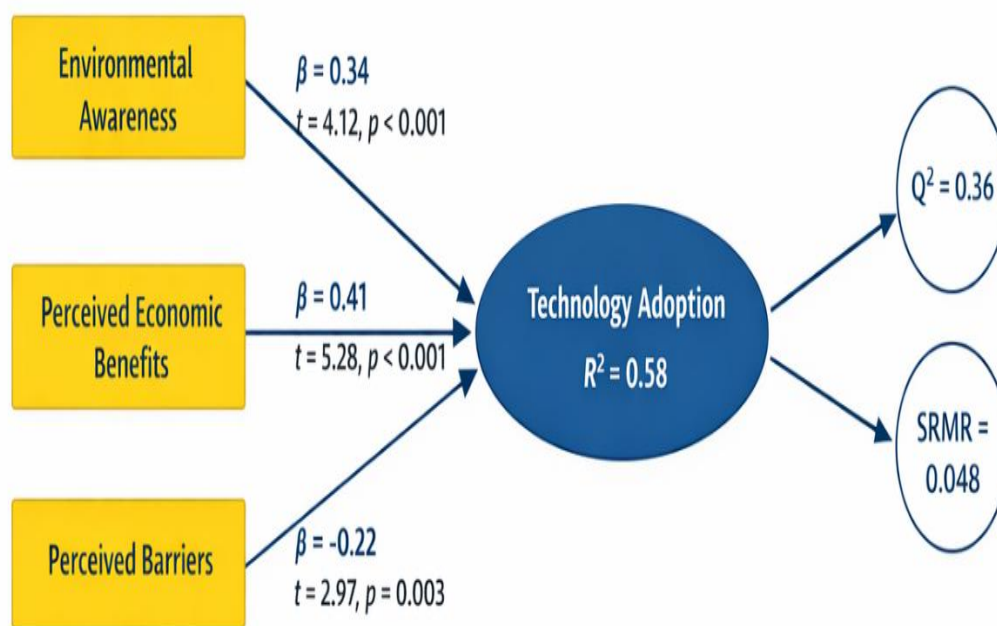


Table 4.5 Path Coefficients and Hypothesis Testing

Hypothesis	Relationship	$\beta$	t-value	p-value	Result
H1	EA → TA	0.34	4.12	0.001	Supported
H2	EB → TA	0.41	5.28	0.001	Supported
H3	PB → TA	-0.22	2.97	0.003	Supported

The structural model results demonstrate that all proposed relationships between the independent variables and technology adoption are statistically significant and meaningful. Environmental awareness (H1) shows a positive and significant influence on technology adoption ( $\beta = 0.34$ ,  $t = 4.12$ ), indicating that individuals with greater awareness of environmental issues are more inclined to adopt nanotechnology in alloy production. This suggests that sustainability consciousness plays an important role in shaping adoption behavior. Similarly, economic benefits (H2) exhibit the strongest positive effect on technology adoption ( $\beta = 0.41$ ), highlighting that perceived financial advantages such as cost efficiency, improved productivity, and long-term profitability are the most influential factors driving adoption decisions within industries. In contrast, perceived barriers (H3) have a negative yet significant impact

on technology adoption ( $\beta = -0.22$ ), implying that concerns related to high costs, technical complexity, and lack of expertise can hinder the adoption process. Although this negative effect is comparatively weaker than the positive influence of economic benefits and environmental awareness, it remains an important factor that cannot be overlooked. Overall, the findings confirm that all three hypotheses are supported, indicating a well-structured model in which both motivating factors (economic benefits and environmental awareness) and inhibiting factors (perceived barriers) collectively shape the adoption of nanotechnology in sustainable alloy production.

**Table 4.6 Coefficient of Determination ( $R^2$ )**

Construct	$R^2$
Technology Adoption (TA)	0.58

The  $R^2$  value of 0.58 indicates that 58% of the variation in Technology Adoption is explained by Environmental Awareness, Economic Benefits, and Perceived Barriers. This is considered a moderate to strong explanatory power, suggesting that the model effectively captures the key factors influencing adoption behavior.

**Table 4.7 Effect Size ( $f^2$ )**

Relationship	$f^2$
EA $\rightarrow$ TA	0.15
EB $\rightarrow$ TA	0.21
PB $\rightarrow$ TA	0.10

Effect size analysis shows: Economic Benefits (EB) has a medium effect, confirming its dominant role. Environmental Awareness (EA) has a moderate effect. Perceived Barriers (PB) has a small but meaningful effect. This reinforces that economic considerations are the most influential factor in adoption decisions.

**Table 4.8 Predictive Relevance ( $Q^2$ )**

Construct	$Q^2$
Technology Adoption	0.36

The  $Q^2$  value of 0.36 indicates strong predictive relevance of the model. This means the model not only explains relationships but also has good predictive capability for future observations.

The overall findings of the analysis indicate that economic benefits emerge as the most influential driver of nanotechnology adoption, highlighting the critical role of cost efficiency, productivity gains, and profitability in shaping industry decisions. Environmental awareness also plays a significant and positive role, suggesting that individuals and organizations with a stronger understanding of environmental sustainability are more likely to adopt innovative technologies such as zinc oxide nanoparticles in alloy production. At the same time, perceived barriers negatively affect adoption behavior, as concerns related to high costs, technical complexity, and

limited expertise can restrict implementation; however, these barriers do not outweigh the positive influence of economic and environmental factors. Furthermore, the model demonstrates strong explanatory and predictive power, indicating that the selected variables effectively capture and explain the key determinants influencing technology adoption within the context of sustainable nanotechnology.

### Discussion

In the framework of the circular economy, the principal aim of this study was to investigate the social and economic obstacles that impede the utilisation of zinc oxide (ZnO) nanoparticles in the fabrication of sustainable alloys. The research employed a quantitative methodology, incorporating SmartPLS analysis to examine the influence of environmental awareness, perceived economic advantages, and perceived obstacles on technology adoption. The measuring model demonstrated considerable reliability and validity. The structural model demonstrated robust interconnections across variables, exhibiting significant explanatory power ( $R^2 = 0.58$ ), substantial predictive ability ( $Q^2 = 0.36$ ), and no concerns regarding multicollinearity ( $VIF < 3$ ). These results provide us a great opportunity to discuss about the social and technical variables that affect how people use nanotechnology.

The findings indicate that awareness of one's environment positively and statistically significantly influences the likelihood of adopting new technology ( $\beta = 0.34$ ,  $p < 0.001$ ). This shows that firms' actions are greatly affected by how aware they are of sustainability. The descriptive statistics support this conclusion, as a high mean value (3.89) indicates that respondents are largely aware of environmental issues and the capacity of nanotechnology to address them. This study corroborates previous studies demonstrating that environmentally responsible organisations are more predisposed to adopt sustainable technologies (Zhu, Sarkis, & Lai, 2008; Kirchherr et al., 2017). Aqsa et al. (2026) state that ZnO nanoparticles remain longer and can clean themselves. This can help keep costs down for replacing and maintaining materials, which is excellent for the economy and the environment in circular manufacturing models. The tiny impact size ( $f^2 = 0.15$ ) suggests that being aware of what's going on around you is a key part of making decisions about adoption, but not the most crucial one. If businesses know how to manage resources better, generate less waste, and make things last longer, they are more likely to use ZnO nanoparticles to make alloys in a circular economy. The validity results ( $AVE > 0.50$ ) confirm the accuracy of the environmental awareness measurement, hence enhancing the reliability of this relationship. Also, the fact that there is no multicollinearity ( $VIF = 2.10$ ) means that this construct explains adoption behaviour on its own.

The perceived economic benefits were the most dependable predictor of individuals' propensity to embrace the technology ( $\beta = 0.41$ ,  $p < 0.001$ ). The descriptive analysis corroborated this by assigning it the highest mean value of 4.02. This indicates that the poll respondents prioritise the financial and performance-related advantages of nanotechnology. The effect size ( $f^2 = 0.21$ ) shows that economic benefits have a moderate to large effect, making them the most important factor in the model. This aligns with Rogers' (2003) theory of the diffusion of innovation, which posits that

relative advantage is a crucial determinant in the adoption process. The results suggest that ZnO nanoparticles are thought to improve alloys' properties, such as their strength, resistance to corrosion, and efficiency. This leads to lower maintenance costs and higher output (Kumar & Krishnamoorti, 2010; Sirelkhatim et al., 2015). The model's high explanatory power ( $R^2 = 0.58$ ) suggests that economic rewards and other things have a substantial effect on how people decide to buy new things. The low VIF value of 2.35 also suggests that economic benefits don't overlap too much with other predictors, which makes their unique contribution stronger. This illustrates that most businesses are operated by common sense. People are more likely to undertake activities that are good for the environment if they can also make money.

The findings demonstrate that perceived restrictions have a substantial and detrimental effect on technology adoption ( $\beta = -0.22$ ,  $p = 0.003$ ). The descriptive statistics (Mean = 3.45) demonstrate that most people are somewhat worried, but the high standard deviation (0.82) shows that they don't all agree on what the problems are. The effect size ( $f^2 = 0.10$ ) is not particularly big, but it is still important. This means that people might not be able to accept it as easily if it costs too much, they don't know enough about technology, or they don't know the rules. This finding corroborates previous studies indicating that perceived dangers and complexity can impede the diffusion of new technology (Nel et al., 2006; Sharma et al., 2016). The overall model findings, on the other hand, reveal that the bad consequences of difficulties are not worse than the favourable benefits of being aware of the surroundings and making money. The low VIF score (1.89) shows that the perceived impediments are not statistically the same. This shows that their harmful effects aren't because they're like other buildings. These results suggest that giving people training, money, and clear rules can make it easier to deal with problems. The structural model is quite good at making predictions and explaining phenomena. With a  $R^2$  value of 0.58, the model can explain 58% of the differences in how people use technology. This is a huge deal for research in the social sciences. The  $Q^2$  value of 0.36 also suggests that the model does a decent job of forecasting how people will use it in the future. The route coefficients are also more dependable because there is no multicollinearity. The findings indicate that technology adoption is influenced by a combination of economic, environmental, and behavioural factors. This backs up the premise that sustainable innovation is both social and technological.

### Conclusion & Recommendations

This study provides actual data on the social and economic issues influencing the application of nanotechnology in the development of sustainable alloys. The findings indicate that individuals' comprehension of the environment, perceived economic incentives, and perceived limitations significantly influence their adoption decisions. When businesses use new technology, they think about how much it will cost, how much work it will do, and how much money they will make. They know that the most essential thing is to make money. Being conscious of the environment is also important because it makes individuals more likely to do things that are good for it. On the other hand, perceived impediments make it less likely that people will adopt

something, although not as much as positive drivers do. The study demonstrates that ZnO nanoparticles align with the principles of a circular economy by extending material longevity, minimising waste, and enhancing resource efficiency. The model's outstanding capacity to clarify and forecast conduct reveals that the chosen variables effectively capture the primary aspects that determine adoption behaviour. The findings indicate that the use of nanotechnology is not only a technological decision; it is a complex social and economic process wherein financial incentives, environmental consciousness, and perceived risks converge to influence industrial operations.

Governments and other groups should help people learn more about the environment by offering classes and training. If more people learn about sustainability and nanotechnology, they will be able to use them more. This is because being conscious of the surroundings has such a large impact on the good things that happen. Offer Financial Incentives: Paying people is the best way to convince them to do something, so the government should offer small and medium-sized businesses (SMEs) money in the form of subsidies, tax breaks, and other types of financial help to help them get started. If you give people prizes for doing things that are good for the environment, they will keep doing them for a long time. Improve technological Skills: Building training centers and letting schools and businesses work together can help solve technological problems. It's easier to get things done and less shocking when people share what they know and learn new things. Make the regulations clear: Clear and consistent rules for nanomaterials can help people understand what's going on and feel better about the field. People should utilise them if they follow the law and follow standard safety regulations. Encourage Circular Economy Practices: Plans for adopting nanotechnology should include rules that encourage recycling, smart use of resources, and creating things in a way that doesn't hurt the environment. Advancing eco-friendly nanotechnology can be advantageous for the economy and the environment. Future Directions: Additional research should explore longitudinal studies to evaluate the enduring effects of ZnO nanoparticles, conduct comparative analyses with other nanomaterials, and implement qualitative assessments of stakeholder perspectives. Adding more details to the model, like how ready the organization is or how much pressure there is from regulators, might make it easier for individuals to understand.

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