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Utilisation of Metal Oxide Nanoparticles in Enhancing the Mechanical Properties of Waste Polypropylene Nanocomposites

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Abstract

The increasing amount of polymeric wastes, especially polypropylene (PP), presents serious environmental problems because it is not biodegradable. This work investigated the development of titanium dioxide (TiO_2) and barium oxide (BaO) nanoparticles as reinforcing agents to improve the mechanical properties of waste polypropylene (wPP) nanocomposites. The BaO and TiO_2 nanoparticles were prepared via a controlled co-precipitation technique. Thereafter, these nanoparticles were mixed with waste polypropylene using melt blending to create nanocomposites of varying weight compositions. The final products underwent mechanical testing, which included measurements of elastic modulus, impact resistance, tensile strength, flexural strength, and hardness. These mechanical test results indicated that sample A (96 g wPP + 4 g TiO_2) has the highest tensile strength of 11.38 MPa with sample D (88 g wPP + 12 g BaO), 11.20 MPa; compared to 9.38 MPa of the control sample (wPP); sample E (88g wPP + 12 g BaO) has the highest elastic modulus of 0.83 J/mm^2 compared to that of the control sample (0.77 J/mm^2) and then sample B (92 g wPP + 8 g TiO_2) with elastic modulus of 0.76 J/mm^2. Other mechanical properties such as hardness value and flexural strength followed the same pattern. These results demonstrated that incorporation of TiO_2 and BaO nanoparticles into wPP improved its mechanical properties which was observed to increase with increase in weight percentage of the nanoparticles incorporated. The results also indicated better interfacial adhesion actions of BaO and TiO_2 within the polymer matrix, accounted for the notable improvements of these parameters. This study therefore depicts another sustainable way of plastic wastes re-utilization.

Keywords: polypropylene; waste polypropylene; Barium Oxide BaO; Titanium Oxide TiO_2; impact resistance test.

1.0 Introduction

A common thermoplastic polymer, polypropylene (PP) is renowned for its excellent tensile strength, strong chemical resistance, low cost, and good mold ability. Because of these qualities, it can be used in a variety of products, including textiles, household goods, automotive parts, and packaging [1]. However, because polypropylene waste is difficult to recycle

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effectively and is not biodegradable, its effects on the environment are starting to become serious concerns. Polypropylene makes up a significant amount of the 350 million metric tons of plastic waste produced annually worldwide [2]. Unfortunately, only 9 % of plastic waste is recycled; the majority is either dumped in landfills or burned, which has a significant negative impact on the environment [2]. Due to the tendency of conventional mechanical recycling techniques to deteriorate its mechanical and thermal properties, recycling polypropylene poses challenges. The performance of the polymer is limited by this degradation, particularly when the recycled material is used repeatedly [3]. Enhancing recycled polypropylene's qualities is crucial to overcoming this obstacle and ensuring its continuous use in higher-performance applications. Creating polypropylene polymer nano composites (PPNCs), which incorporate nanomaterial's—particularly metal oxide nanoparticles (MO NPs)—into the polymer matrix, is one promising strategy [2, 3].

Metal oxides, including cerium oxide (CeO_2), iron oxide (FeO_3), barium oxide (BaO), and titanium dioxide (TiO_2), have been shown to dramatically improve the mechanical strength, thermal stability, and resistance to UV degradation of polymers [5]. Because of these enhancements, metal oxide nanoparticles are especially well-suited for high-performance uses. The performance of recycled polypropylene has been improved by these nanoparticles because of their large surface area, chemical stability, and ability to alter material properties at the nanoscale [4]. TiO_2 and BaO nanoparticles, for instance, have been demonstrated to improve polypropylene's tensile strength, impact resistance, and thermal stability, making it more resilient for use in packaging and automotive components. Additionally, these nanoparticles can help lessen the polymer's flammability, which is crucial for applications in construction and electronics. Furthermore, metal oxide nanoparticles like BaO have antibacterial qualities that make them appropriate for use in food packaging and medicine [5].

In addition, the catalytic qualities of metal oxides may help break down polypropylene waste and pave the way for more environmentally friendly recycling techniques [6]. The effectiveness of the metal oxide nanoparticles depends on their proper dispersion and good interfacial interactions with the polypropylene matrix; agglomeration or poor dispersion can negate the advantages of the nanocomposite [6]. Polypropylene is widely used in a variety of applications, including packaging, automotive parts, and textiles, because of its strength, light weight, and chemical resistance. But because PP is not biodegradable and adds to plastic pollution, its waste accumulation presents serious environmental problems [7].

Researchers have been searching for ways to use nanotechnology to improve the qualities of recycled polypropylene in order to address these problems. Titanium dioxide, barium oxide, and aluminum oxide are examples of metal oxide nanoparticles that have potentials as additives in the creation of nanocomposites because of their distinct physicochemical characteristics, which include high surface area, thermal stability, and catalytic activity. The goal of using metal oxide nanoparticles in waste polypropylene nanocomposites is to enhance important characteristics such as mechanical, thermal for re-utilization; and barrier and degradation properties for easier recycling. This prompted the need to investigate how these sprawling wastes of polypropylene could be developed into economically viable materials suitable for different applications.

2.0 Materials and methods

2.1 Sample collection and preparation

Polypropylene wastes from waste buckets with recycling code '5' were gathered from a trash dumps and plastic waste collected centres in Mando market, Igabi Local area, Kaduna State, Nigeria. After a thorough washing and cleaning with detergent and water to get rid of any dirt or other contaminants, the collected polypropylene waste was dried. To make handling easier, the waste was subsequently mechanically shredded into smaller pieces in accordance with the work of [8, 9]. In order to prepare the PP waste solution; 96, 92, 88, 84, and 80 g of shredded polypropylene waste were dissolved in 50 cm^3 for the 96g and 92g due to their higher percentage of polymer material, while 88g, 84g, and 80g were dissolved in 45 cm^3 tetrachloroethylene in a conical flask (1000 ml) and continuously stirred for 20 minutes using a magnetic stirrer. In order to ensure total dissolution and create a homogenous solution, the mixture was then heated to 200 °C for 10 minutes. The synthesized metal nanoparticles (TiO_2 and BaO) of 4, 8, 12, 16 and 20 g, were then added respectively. Thereafter, the materials were then combined with the waste PP solution and left for five to ten minutes to create a uniform solution [8].

2.2 Synthesis of Nanoparticles

Titanium oxide (TiO_2) and barium oxide (BaO) nanoparticles were synthesized using the wet chemical precipitation method. 0.4 M sodium bicarbonate was added dropwise to a 0.2 M barium nitrate solution while being continuously stirred for two hours to finish the reaction. After letting the precipitate settle overnight, it was filtered and repeatedly cleaned with distilled water to get rid of any remaining bicarbonate [7]. To create BaO nanoparticles, the precipitate was first dried for an hour at 80 °C in an oven and then calcined at 1250 °C for one hour. Sol-gel method was used to synthesize barium oxide nanoparticles. A titanium isopropoxide, was first mixed with a mixture of ethanol and water. This resulted in the formation of a colloidal suspension

of reactive titanium species. Deionized water was then added gradually while being vigorously stirred to ensure the hydrolysis and condensation process, which resulted in the formation of hydroxyl groups and the expansion of a three-dimensional network [4]. After that, the gel was gently dried at 70 °C to get rid of the remaining solvent with the formation of an intermediate product known as xerogel. The dried xerogel was finally calcined at 400 °C to produce crystalline TiO_2 nanoparticles. The pH of the solution was maintained at 7.8 to obtain pure anatase phase at 400 °C for 2 hours [6].

2.3 Blending and Compounding of Nanoparticles.

A steel mould of dimensions: 120 x 180 mm, 3 mm thick, and 5 mm high, used in the casting the mixture of the synthesized BaO nanoparticles and the solution of waste polypropylene with adequate mixing to ensure uniform dispersion of the nanoparticles within the polypropylene matrix. The composite material was then allowed to cool for approximately five minutes and finally removed from the mould. The procedure was repeated for TiO_2 until all the required composites were obtained [8].

2.4 Mechanical Property Test

2.4.1 Hardness Test

Vickers Hardness Test Machine Model (MV1-PC) Capacity (0.3 kgf), ASTM E-384 standard was used to evaluate the hardness value of the nanocomposites. The foundation of the composites hardness test is the surface's relative resistance to indentation by an indenter of a given size under a given load [9]. The shore hardness of samples measuring 20 mm by 20 mm by 3 mm was measured using a Vickers hardness test machine (MV1-PC). The samples' hardness was ascertained by averaging the results of three measurements taken at different locations [8].

2.4.2 Flexural Strength

The flexural strength of the nanocomposites were carried out using Universal Testing Machine Capacity (100KN) according to ASTM D-790 standard Model (Cat. Nr. 261). The flexural strength and flexural modulus were calculated using equations (1) and (2) respectively.

$$\frac{3FL}{2bt^2} \quad (1)$$

$$\frac{FL^3}{4bt^3d} \quad (2)$$

Where:

l = length of specimen span between support (mm);

P = maximum deflection force (N);

b = width of specimen (mm);

t = thickness of specimen (mm).

F = maximum load

L is the distance between the supports

d is the deflection (in millimeters) [9].

2.4.3 Impact Test

The impact strength of the nanocomposites were investigated via Model (Cat. Nr. 412) of the

Charpy Impact Testing Machine Standard (15 J) capacity (ASTM E-23). The impact test determines a material's toughness by measuring its capacity to absorb energy during a sudden force or shock [10].

2.4.4 Tensile Test

The ASTM D 638 recommended method was used to determine the samples' tensile test results. After being machined into the shape of a dumbbell, the samples were put into a computerized Instron universal tensile testing machine 3369 model, which assessed the elastic modulus and tensile strength [3] .

3.0 Results and Discussion

3.1 Hardness Value of BaO and TiO_2 filled waste PP nanocomposites

The hardest value results demonstrated that in comparison to the control sample, the addition of TiO_2 and BaO nanoparticles considerably increased the hardness of recycled PP as could be observed in figures 1 and 2. Sample C (80g PP + 20g TiO_2) has the highest hardness value (73.73) which is higher than that of the BaO nanocomposite at the same loading. This is consistent with research by [10]. According to the WHO, metal oxide nanoparticles' high surface area and robust interfacial bonding enhance mechanical properties. TiO_2's superior dispersion and compatibility with the PP matrix may be the reason for its superior performance over BaO, according to [5]. However, at the same nanoparticles loading (Sample F with 20g BaO) resulted in lower hardness value which could be due to agglomeration which lowers interfacial bonding—a phenomenon also noted by [7], in similar nanocomposites.

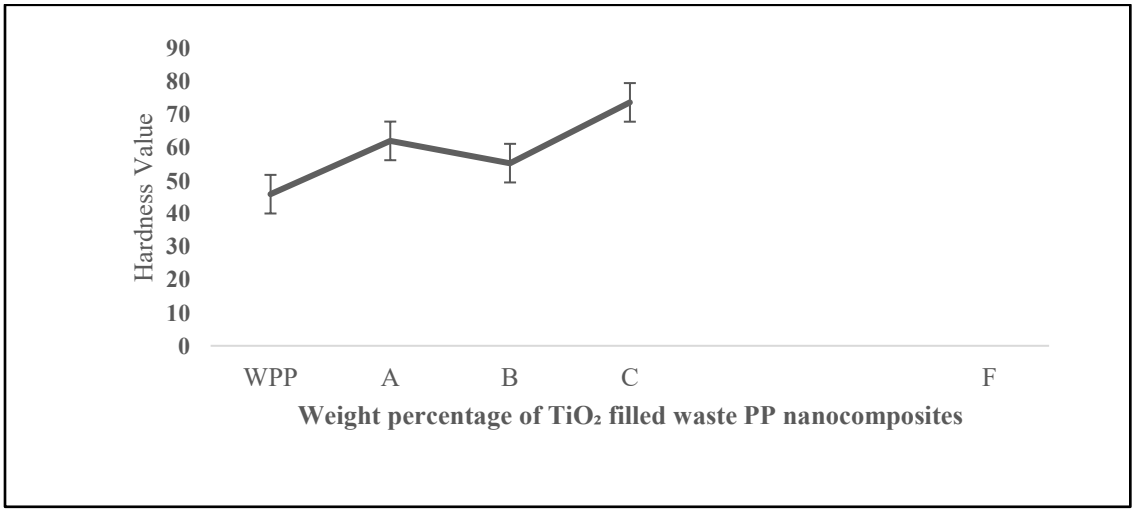


Figure 1: Effect of TiO_2 nanoparticles on the hardness result of waste PP nanocomposites.

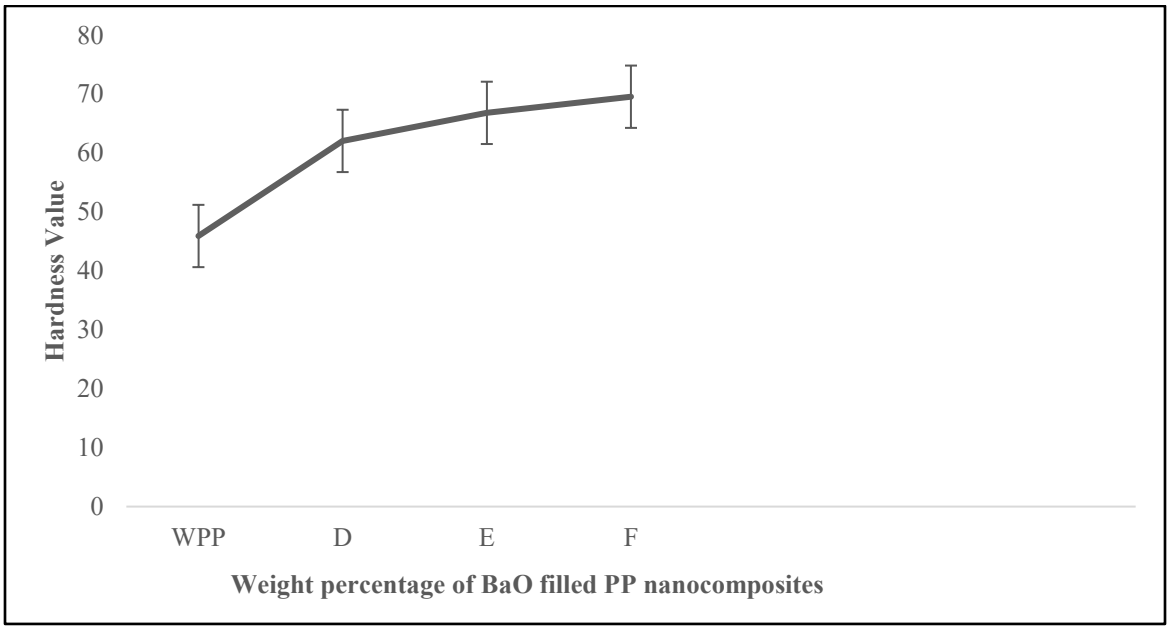


Figure 2: Effect of BaO nanoparticles on the hardness result of waste PP nanocomposites

3.2 Impact energy of BaO and TiO_2 filled waste PP nanocomposites

The addition of TiO_2 and BaO nanoparticles considerably improved the impact resistance of recycled PP in comparison to the control sample, as demonstrated by the impact test results in Figures 3 and 4. The samples with the highest impact resistance were A (96 g PP + 4g TiO_2) and D (88 g PP + 12 g BaO), indicating that toughness is enhanced by moderate nanoparticle concentrations. This enhancement can be attributed to the nanoparticles' capacity to both absorb and release energy, according to [11]. In contrast, Sample C (80g PP + 20g TiO_2) displayed decreased impact resistance, which might be the result of brittleness brought on by overloading the nanoparticles in accordance with [12], who noted that excessive filler content can restrict polymer chain mobility, reducing ductility.

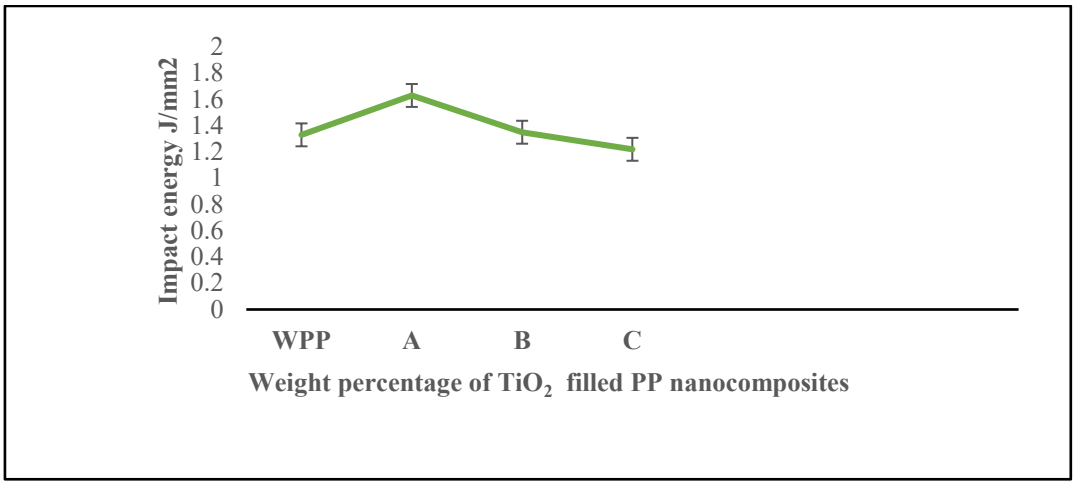


Figure 3: Effect of TiO_2 nanoparticles on the impact resistance of waste PP nanocomposites.

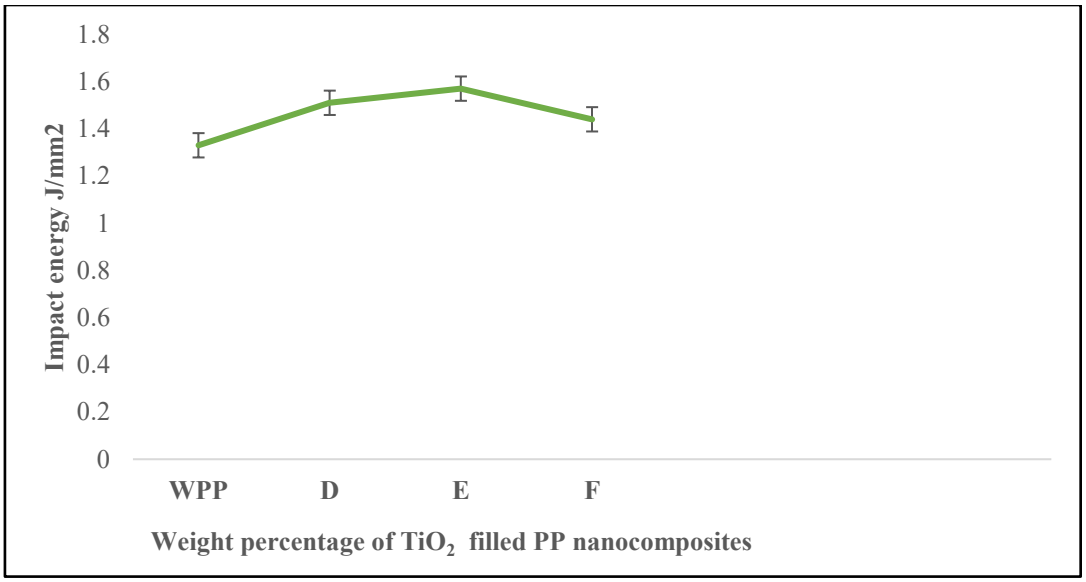


Figure 4: Effect of BaO nanoparticles on the impact resistance of waste PP nanocomposites

3.3 Tensile strength of BaO and TiO_2 filled waste PP nanocomposites

Figure 5 and 6 depict the tensile strength results of BaO and TiO_2 filled waste PP nanocomposites. The tensile strength of recycled PP was observed to be improved by the addition of TiO_2 and BaO nanoparticles compared to the control sample (waste PP) which has a value of (9.38 MPa). Samples A (96g rPP + 4g TiO_2) and D (88g rPP + 12g BaO) had the highest tensile strength (11.84

MPa and 11.20 MPa) respectively. This improvement supports the observation that stress transfer within the polymer matrix was improved by evenly distributed nanoparticles. However, a decline in tensile strength was observed with Sample C (80 g rPP + 20 g TiO_2) which had a value of 7.97 MPa; this could most likely be as a result of inadequate dispersion or nanoparticle agglomeration of the TiO_2 in the recycled PP as noted by other authors [10, 11].

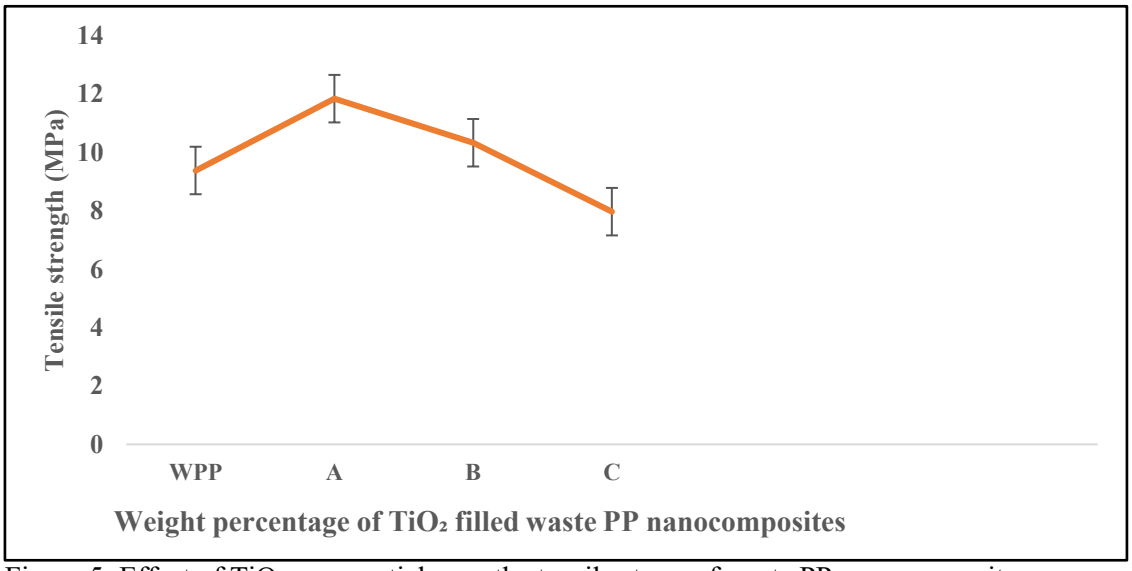


Figure 5: Effect of TiO_2 nanoparticles on the tensile stress of waste PP nanocomposites.

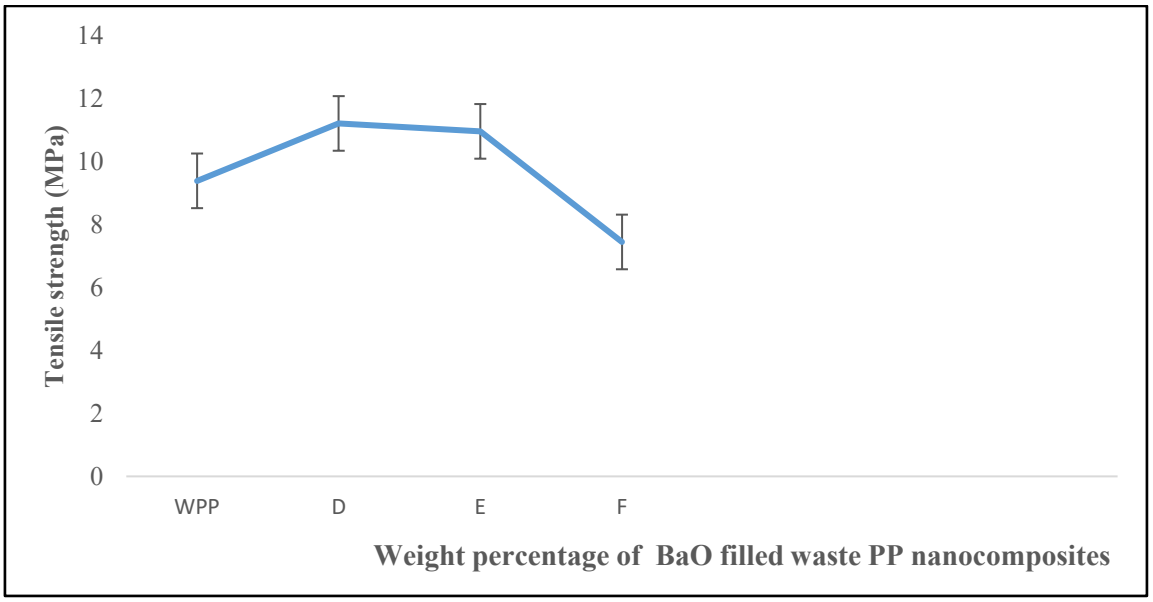


Figure 6: Effect of BaO nanoparticles on the tensile strength of waste PP nanocomposites

3.4 Elongation at break of BaO and TiO_2 filled waste PP nanocomposites

Samples A (96 g rPP + 4 g TiO_2) and C (80 g rPP + 20 g TiO_2) show the highest elongation 16.62 % and 16.76 %, respectively, indicating improved ductility; this suggests that TiO_2 nanoparticles enhance flexibility by reducing crystallinity defects as could be observed in figures 7 and 8 [13]. Sample F (80 g rPP + 20 g BaO) with elongation at break value (10.74 %,) on the other hand, displayed lower elongation at break value; this may likely be as a result of BaO-induced brittleness, which is consistent with findings by [1], According to the WHO, a high filler content limits the mobility of polymer chains.

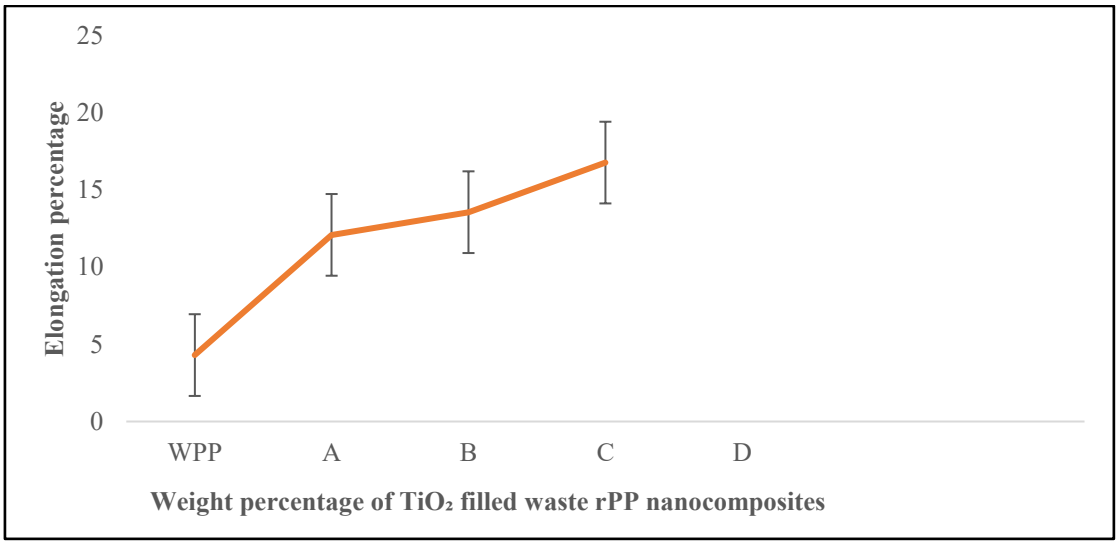


Figure 7: Effect of TiO_2 nanoparticles on the elongation percentage of waste PP nanocomposites

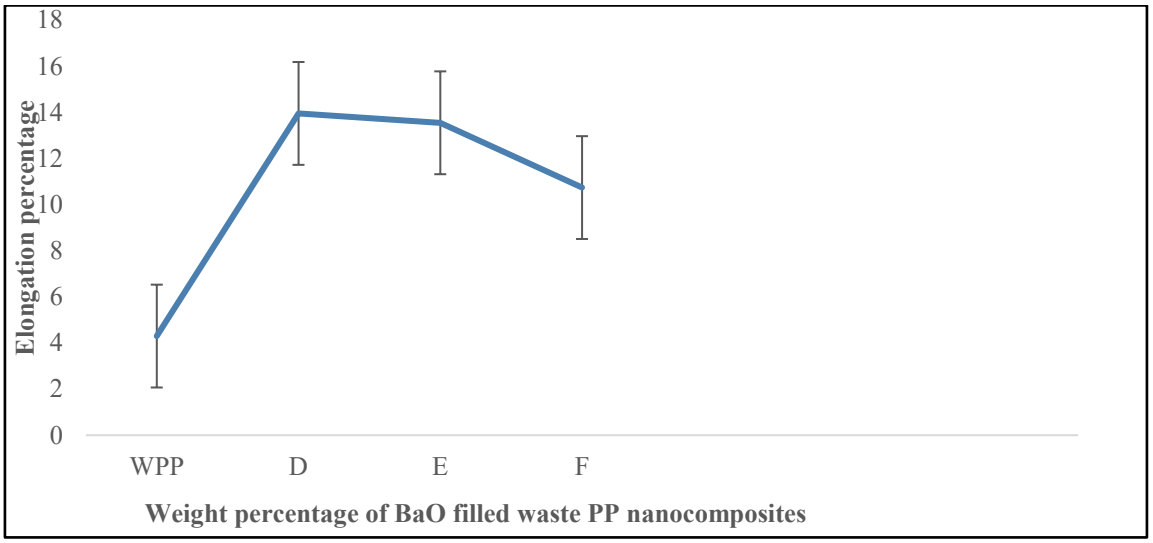


Figure 8: Effect of BaO nanoparticles on the elongation percentage of waste nanocomposites

3.5 Elastic Modulus of BaO and TiO_2 filled waste PP nanocomposites

Sample D (0.80 GPa) had the highest stiffness according to the elastic modulus results in figures 9 and 10, suggesting that incorporation of BaO nanoparticles increase rigidity. This is consistent with the findings of [14] and that made by [19] who reported that reinforcement of waste PP increases its elastic modulus. Sample C (80 g rPP + 20 g TiO_2) had the least elastic modulus value (0.47 GPa), indicating that high TiO_2 loading could compromise the structural integrity of the

polymer in accordance with [6], who noted similar trends in clay-reinforced PP.

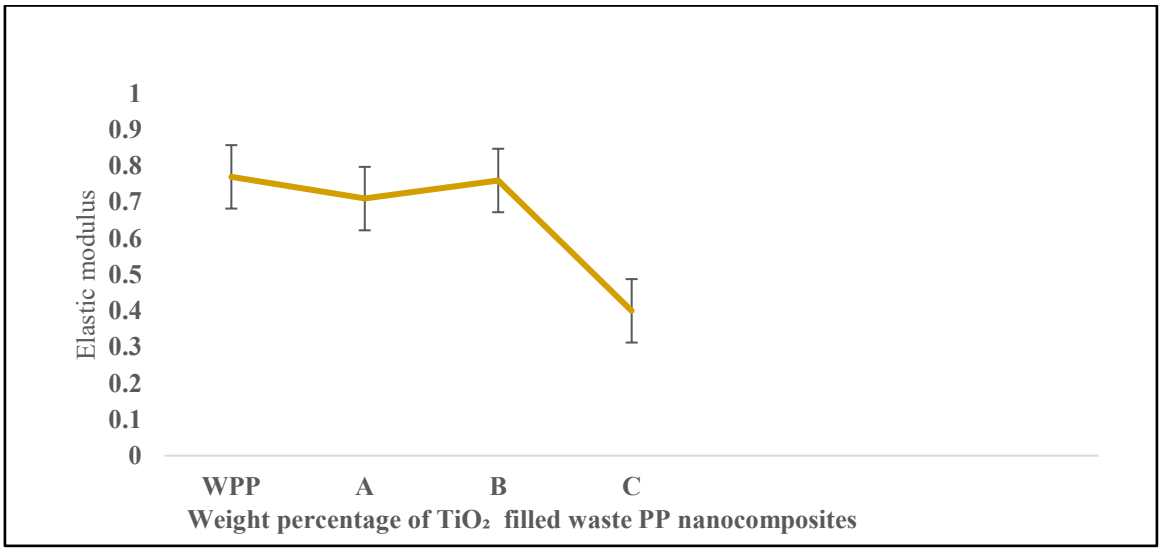


Figure 9: Effect of TiO_2 nanoparticles on the Elastic modulus of waste polypropylene Nano composites

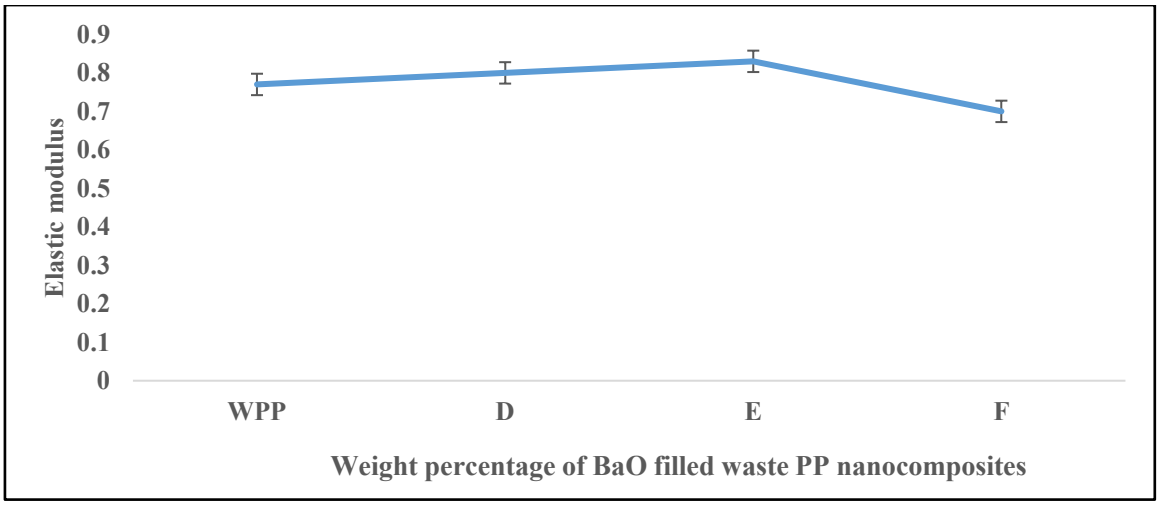


Figure 10: Effect of BaO nanoparticles on the elongation percentage of waste PP nanocomposites

3.6 Flexural Strength of BaO and TiO_2 filled waste PP nanocomposites

Figure 11 and 12 displayed the effect of TiO_2 and BaO nanoparticles addition on the flexural strength of waste PP nanocomposites. The flexural strengths of the waste PP was observed to considerably improve by the addition of TiO_2 and BaO nanoparticles. Sample A (4g TiO_2)

outperformed Sample B (wPP: 10.95 MPa) by achieving the highest flexural strength (15.89 MPa) among the TiO_2 reinforced composites. These results are in agreement with the work of [18] which reported that incorporation of TiO_2improves stress transfer and interfacial bonding in polymer matrices while Sample B (8g TiO_2) showed reduced strength (11.03 MPa), suggesting a decline in flexural strength at higher loadings due to nanoparticle agglomeration [15]. Composites reinforced with BaO (Samples D, E, F): Sample E (16g BaO) demonstrated balanced strength (13.54 MPa), surpassing the control but falling short of TiO_2. BaO may not be as effective at reinforcing as TiO_2 due to its lower aspect ratio [16]. Sample F (20 g BaO) displayed variability (11.37 MPa), suggesting difficulties with dispersion at elevated concentrations. The lowest strength, 9.93 MPa, and brittleness due to an excessive filler content are confirmed by Sample C (20g TiO_2), which also disrupts the polymer matrix [13]. Sample C's modulus (150.0 MPa) is close to that of the control, suggesting that at higher fibre loading, there was decrease in flexural strength. The flexural modulus of sample F (275.5 MPa) surpassed BaO filled counterparts but was less consistent (high standard deviation), likely due to uneven particle distribution [17]. This result was found to be better than that of [18].

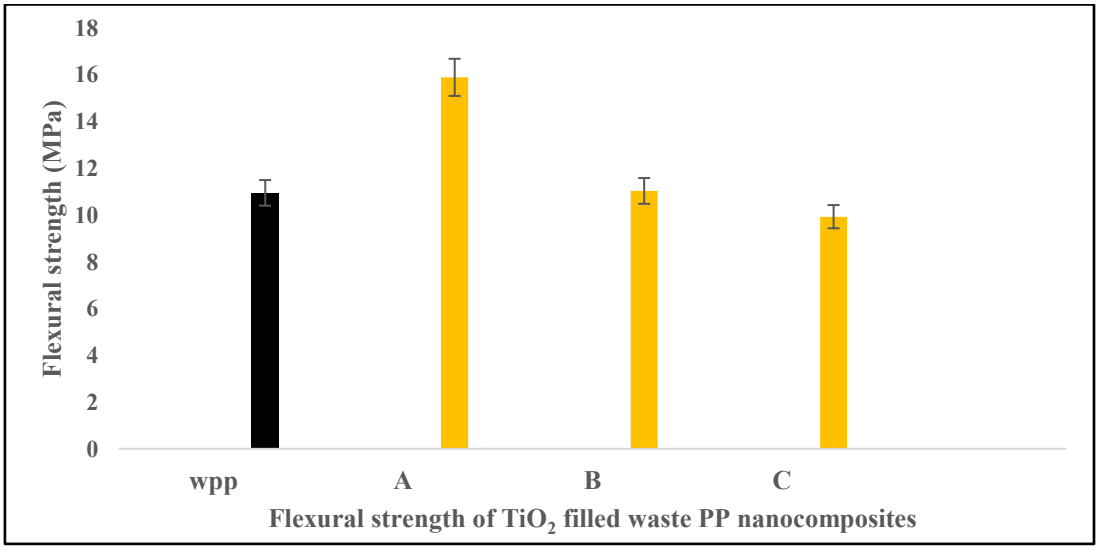


Figure 11: Effect of TiO_2 nanoparticles on the flexural strength of waste PP nanocomposites

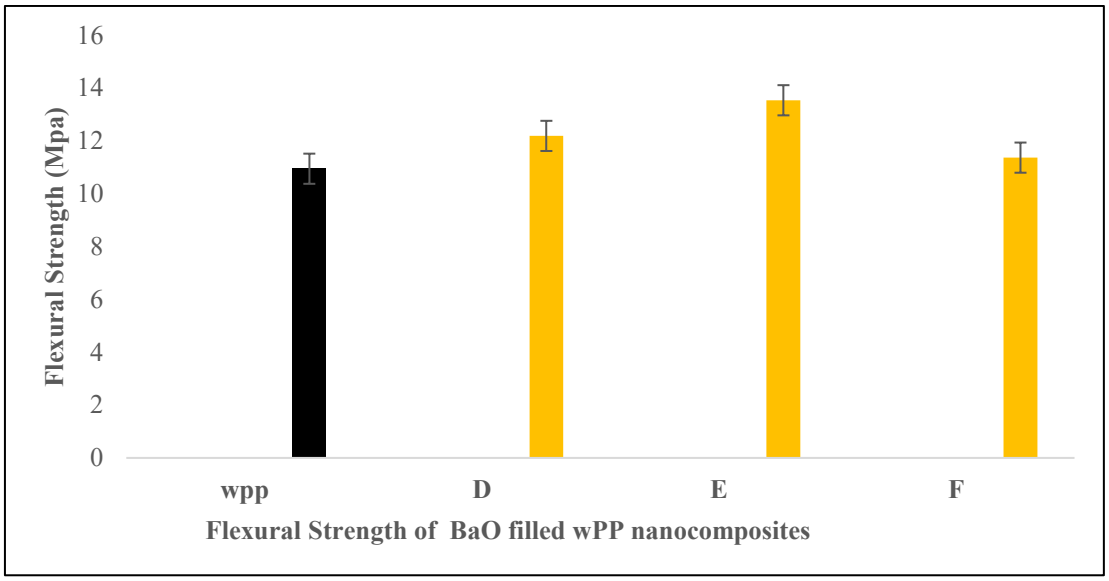


Figure 12: Effect of BaO nanoparticles on the flexural strength of waste PP nanocomposites.

3.7 Flexural modulus BaO and TiO_2 filled waste PP nanocomposites

The Flexural modulus results of the developed nanocomposites are presented in figures 13 and 14. The results showed that TiO_2 and BaO nanoparticles significantly enhanced the flexural modulus test results of recycled polypropylene (PP) compared to the control sample and other related works [7].

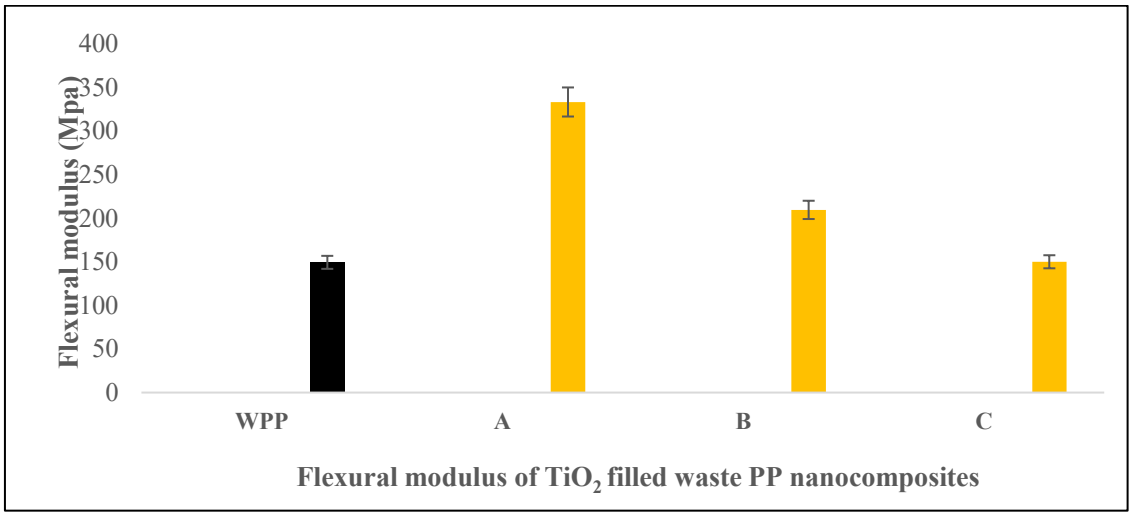


Figure 13: Effect of TiO_2 nanoparticles on the flexural modulus of waste PP nanocomposites

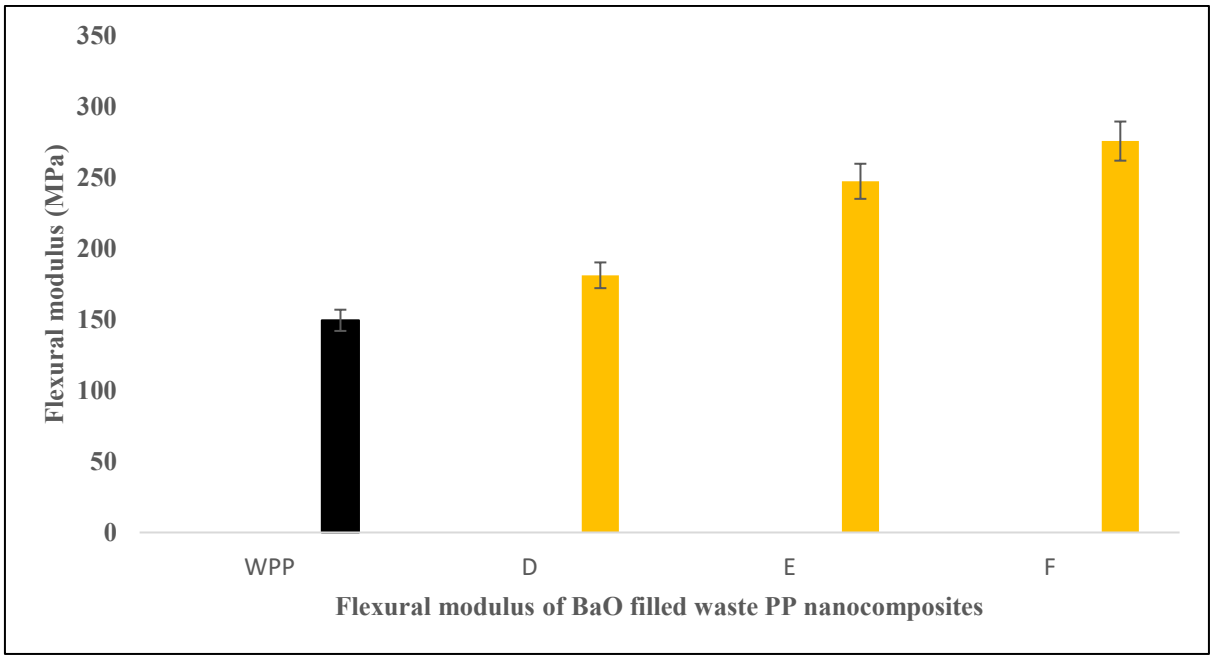


Figure 14: Effect of BaO nanoparticles on the flexural modulus of waste PP nanocomposites.

5.0 Conclusion

The synthesis and use of titanium dioxide (TiO_2) and barium oxide (BaO) nanoparticles as reinforcing agents to improve the structural and functional characteristics of recycled waste PP nanocomposites has been investigated. A regulated co-precipitation technique was used to create BaO and TiO_2 nanoparticles. To create nanocomposites with enhanced performance, these nanoparticles were subsequently mixed with waste PP. The resultant materials underwent extensive mechanical testing, which included tensile strength, flexural strength, impact resistance, and hardness. These mechanical test results indicated that sample A (96 g wPP + 4 g TiO2) has the highest tensile strength of 11.38 MPa with sample D (88 g wPP + 12 g BaO), 11.20 MPa; compared to 9.38 MPa of the control sample (wPP); sample E (88g wPP + 12 g BaO) has the highest elastic modulus of 0.83 J/mm^2 compared to that of the control sample (0.77 J/mm^2) and then sample B (92 g wPP + 8 g TiO_2) with elastic modulus of 0.76 J/mm^2. Other mechanical properties such as hardness value and flexural strength followed the same pattern. These results demonstrated that incorporation of TiO_2 and BaO nanoparticles into waste PP improved its mechanical properties which was observed to increase with increase in weight percentage of the nanoparticles incorporated. In order to establish the end use applications of the developed nanocomposites, there is a need to carry out more

characterizations such as dynamic mechanical analysis (DMA), X-ray diffraction (XRD), thermogravimetric analysis (TGA) and scanning electron microscope (SEM).

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The Data Availability

The data that support the findings of this study are available on request from the corresponding author.

Competing interests

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Compliance with ethics requirement

Not applicable.

Conflict of interest

The authors confirm that this article content has no conflicts of interest.

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