

Sustainable Manufacturing of Lightweight Polypropylene Composite Foams: Mechanical Performance and Cellular Morphology of Micro/Nano Silica Reinforced PP

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Abstract

Sustainable processing of low-density polymers has recently been of increasing interest for engineering purposes where decreased density and increased material efficiency are desired. Polypropylene composites containing micro-silica and nano-silica were fabricated and tested to investigate the effect of filler size on the mechanical performance and cellular structure of the composites. The (PP) -silica composites were produced using a SG-20 twin parallel screw extruder and then compression-moulded into solid cylindrical samples. Subsequently, the compression testing was performed per ASTM D695 standard to evaluate the mechanical properties of the resulting polymer composites. PP composites containing various loadings of micro-silica (0–25 wt%) and nano-silica (0.25–6 wt%) were fabricated to investigate the influence of filler size and concentration on the mechanical properties and cellular morphology of the resulting foams. The resulting samples were then subjected to constrained batch foaming with nitrogen (N₂) at 168 °C and 5000 psi for 10 mins. The resulting compressive properties of (PP) show that silica reinforcement improved the compressive mechanical properties of (PP) composites when at optimal filler loading levels. In terms of the highest compression modulus and strength for micro-silica composites, this occurred at 10 wt%, however when considering the effectiveness of reinforcement from nano-silica composites was only at a concentration of 1.5 wt% because of increased specific surface area and better interaction between the filler and matrix. The solid samples were analysed using scanning electron microscopy (SEM) to investigate the differences in the morphology of the broken edges of composite material and filler particle location, however the foamed samples showed continued improvement in the structure of the cellular material based on their morphology in relation to the addition of silica filler material. Furthermore, the introduction of nano-silica to the foamed sample material provided the smallest, most uniformly shaped cellular structures and demonstrated superior nucleating ability during the foaming process when compared to other foaming agents. The constrained foaming process decreased the sample density from 0.765 g/cm³ to 0.096 g/cm³, representing an 87.5% reduction, and expanded the sample volume by a factor of eight.

Keywords

Polypropylene composite foams, Micro-silica and nano-silica, reinforcement, Constrained batch foaming, Cellular morphology, Mechanical properties, Lightweight material

1. Introduction

(PP) is one of the most widely used thermoplastic polymers because of its low density, good chemical resistance, low cost, and ease of processing (Dorigato 2021; Namazi 2017; Zhang et al. 2022). It is commonly applied in automotive, packaging, construction, and consumer products where lightweight materials with balanced mechanical properties are required (Bukvić et al. 2025; Hou et al. 2019; X. Li et al. 2025). In recent years, growing environmental concerns and the demand for sustainable manufacturing have increased interest in developing lightweight polymer materials that reduce raw material consumption while maintaining functional performance (Akbari et al. 2022; Taub et al. 2019).

Advantages of polymer materials include low density, corrosion resistance, ease of processing, design flexibility, and relatively low manufacturing cost. Their lightweight nature makes them particularly attractive for weight-reduction applications, such as in the transportation and aerospace industries. In addition, polymers provide good electrical and thermal insulation properties and can be easily molded into complex shapes (Al-Zu'bi, Fan, and Anguilano 2022; Alami et al. 2024; Sharma et al. 2026).

These advantages do not come without some inherent limitations. Generally, polymers have lower stiffness, strength, and load-carrying capacities compared to metals. They are also highly susceptible to wear, creep, and degradation when exposed to elevated temperatures or prolonged mechanical loading. Among the failure mechanisms that may be expected in polymer components due to their application under conditions of friction and repeated use, wear ranks first (Chattopadhyay, Pathak, and Santos 2023; Gowthaman et al. 2021; Ravula, Hardin, and Ramamoorthy 2019; et al. 2019).

Polymers materials are used in a wide range of industries due to their property combinations. In the automotive sector, polymer materials are used for interior panels, bumpers, and lightweight structural components. They help reduce the weight of aircraft and improve fuel efficiency when applied in aerospace applications. Construction applies polymer materials in pipes, insulation materials, and coatings. In medical implants, prosthetics, and medical devices, polymer materials are used. Packaging, electronics, consumer products, and energy-related applications also use polymer materials (Chelu and Musuc 2023; Swetha et al. 2023; Upadhyay et al. 2024).

Due to their density, high strength-to-weight ratio, and thermal and sound insulating qualities, polymer foams are recognized as a viable option for lightweight applications. Of the thermoplastic foams, (PP) foam has developed a lot of interest because it is recyclable and can be manufactured at a large quantity through industrial processes (Almufarraj et al. 2024). However, commercially produced PP foams are likely to have limited mechanical characteristics and irregular cellular structures, which can limit their use for challenging engineering applications (Dong et al. 2023; Jacobs, Kemmer, and Keurentjes 2008; Krishnan et al. 2025; Sauceau et al. 2011). One method to improve the mechanical properties of PP foams is to use inorganic fillers like silica particles. Micro-silica and nano-silica are both common reinforcers due to their high rigidity, thermal stability, and ability to enhance the mechanical characteristics of a polymer matrix. The larger surface area of a nano-silica also promotes stronger forces between the filler and matrix and better distribution of stress throughout the composite. Silica particles can also serve as a nucleating agent during the foaming process, allowing for a more consistent cell structure as well as a better overall foam structure (cell morphology).

A silica particle's final property of PP composites and foams depends on the size of the silica particles. Larger-sized silica particles create increased dimensional stability as well as higher levels of rigidity in the sample, while smaller-sized ("nano") silica particles create a higher efficiency for mechanical reinforcement and finer cellular structure ("cell refinement") due to their small size and high surface area compared to larger particles. Therefore, understanding how micro- and nano-silica compare to one another within PP foams allow for an understanding of how to obtain the most desirable [most desirable] mechanical properties and the most uniform cellular (cellular) structure in PP foams (Kargarzadeh et al. 2018; L. Li et al. 2024).

A micromechanical interpretation would say that silica particles in a (PP) matrix can affect stress transfer mechanisms, deformation behavior, and structural stability. The efficiency of reinforcement strongly depends on the size of the particles, the quality of dispersion, and the nature of the interface between the filler and the polymer matrix. Silica particles, when well dispersed, can restrict the mobility of polymer chains and hence improve the efficiency of transferring loads, resulting in increased stiffness and strength. The cellular structure also influences mechanical properties by controlling stress distribution, absorption of energy, and deformation modes. Therefore, the interaction between filler size and cellular morphology needs to be understood for optimizing mechanical performance of lightweight PP composite foams and broadening their application area to structural and engineering applications (Chelu and Musuc 2023; Swetha et al. 2023).

Therefore, this research evaluates/produces lightweight foam composite plates using (PP) reinforced with micro- and nano-silica through conducting extrusion foaming followed by batch foaming. The evaluation was conducted on the mechanical properties of the solid and foamed materials and the pore structure including pore size, pore wall thickness, and expansion ratio. The results of this study should contribute to the replacement of current manufacturing practices for lightweight polymer composite manufacturing into engineering applications with less impact on the environment.

Although polypropylene (PP) composite foams have been widely studied, limited research has directly compared the effects of micro-silica and nano-silica fillers under identical processing conditions. In particular, the influence of filler size on both the mechanical properties of solid composites and the cellular morphology of constrained batch-foamed PP structures remains insufficiently understood.

The novelty of this work lies in the systematic comparison of micro- and nano-silica reinforced PP composites produced using extrusion, compression molding, and constrained batch foaming. The study evaluates the effects of filler size on mechanical performance, density reduction, volume expansion, and cellular morphology.

The objective of this research is to identify the optimum silica type and loading for improving the mechanical and foaming behavior of PP composites and to provide insights into the role of particle size in the development of lightweight polymer foams.

2. Material and Methodology

In this study, polypropylene (PP) homopolymer, specifically Luban HP1102K supplied by OQ, was used as the base polymer matrix. This grade features a melt flow rate of 3.4 g/10 min (ASTM D1238, 230 °C/2.16 kg) and a density of 0.90 g/cm³, and is primarily designed for applications such as raffia, tapes, and strapping. Micro-sized silica filler was obtained from Adwan Chemical Industries Company Limited (Saudi Arabia), with an average particle size of 75

microns, irregular morphology, and a density of 0.901 g/cm³, based on the supplier's datasheet. Nano-sized silica (TSP-L802) was sourced from Nanjing Tansail Advanced Materials Co., Ltd. (China). This nanosilica had a particle size of approximately 20 nm, a purity of 99%, a surface area of 200 m²/g, a tapped density of 0.15 g/cm³, and was characterized as oleophilic, hydrophobic, and anti-settling (Al-Mufarraji et al. 2026). Nitrogen (N₂) gas with a purity of **99.5% - 99.9%** supplied by Oman Industrial Gas Co. LLC, was used as the physical blowing agent during the constrained batch foaming process. The high gas purity ensured consistent saturation conditions and reliable foam formation.

Table 1 Formulations of PP/Micro-Silica Composite Samples

Silica Content (wt%)	Total Batch Mass (g)	Silica (g)	PP (g)
0	500	0	500
1	500	5	495
3	500	15	485
5	500	25	475
10	500	50	450
15	500	75	425
20	500	100	400
25	500	125	375

Table 2 Formulations of PP/Nano-Silica Composite Samples

Silica Content (wt%)	Total Batch Mass (g)	Silica (g)	PP (g)
0	500	0	500
0.25	500	1.25	498.75
0.50	500	2.50	497.50
1.0	500	5.00	495.00
1.5	500	7.50	492.50
3.0	500	15.00	485.00

Tables 1 and 2 summarize the formulations used for the preparation of PP composites reinforced with micro- and nano-silica fillers. The filler content was systematically varied to investigate the influence of silica particle size and concentration on the mechanical and foaming behavior of the composites. For the micro-silica series, filler loadings ranged from 0 to 25 wt%, while the nano-silica series contained 0.25 to 6 wt% filler. A constant total batch mass of 500 g was maintained for all formulations by adjusting the PP content accordingly. These formulations enabled a comprehensive evaluation of the effects of filler type and loading on composite performance.

The overall experimental procedure is illustrated in Figure 1 and was designed to investigate the effect of micro- and nano-silica reinforcement on the mechanical performance and cellular morphology of (PP) composite foams.

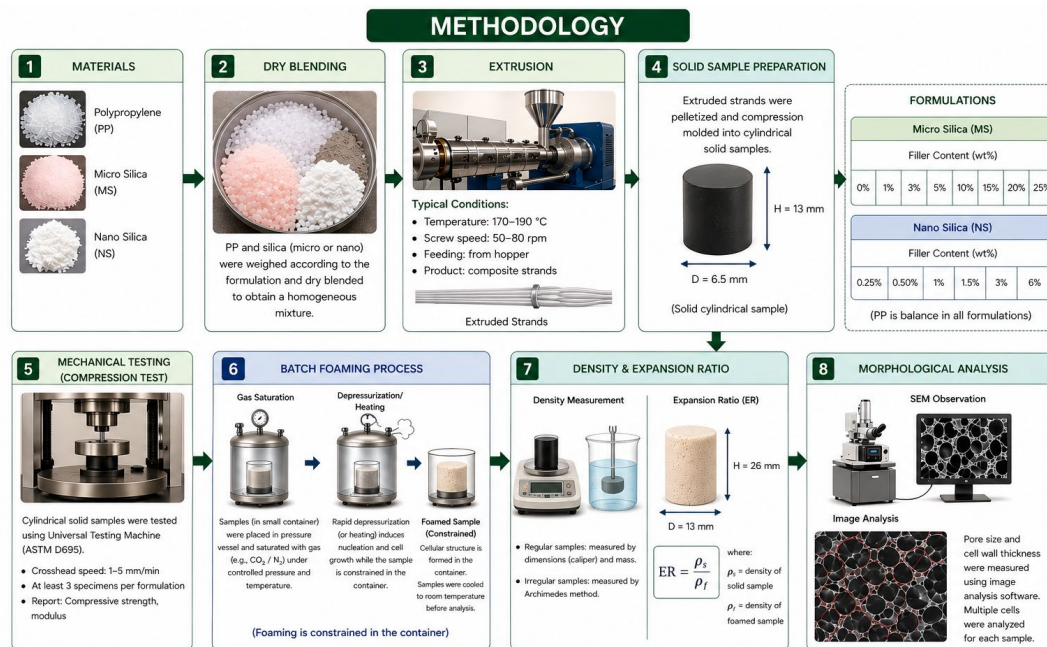


Figure 1. Experimental methodology for preparation of micro/nano silica reinforced polypropylene composites using twin-screw extrusion, compression molding, constrained batch foaming, mechanical testing, density measurement, and SEM morphological characterization.

Several compositions were prepared to study the effect of filler type and loading on the properties of polypropylene composites. Micro-silica was added at levels of 0, 1, 3, 5, 10, 15, 20, and 25 wt%, while nano-silica was added at 0.25, 0.50, 1, 1.5, 3, and 6 wt%, with the remaining balance being PP. The materials were first dry blended to aid in achieving uniform distribution of the filler and then compounded with an SG-20 twin parallel screw extruder from Foshan Nanhai Jingdong Machinery Co., Ltd. to enhance dispersion of the filler within the polymer matrix. The extruded strands were pelletized and then compression molded into cylindrical specimens using a hydraulic press at a molding pressure of 4 tons. After molding, the samples were cooled in the mold using a water-cooling system that is attached to the upper and lower platens of the press to allow for solidification to take place under conditions of control and stability in three dimensions.

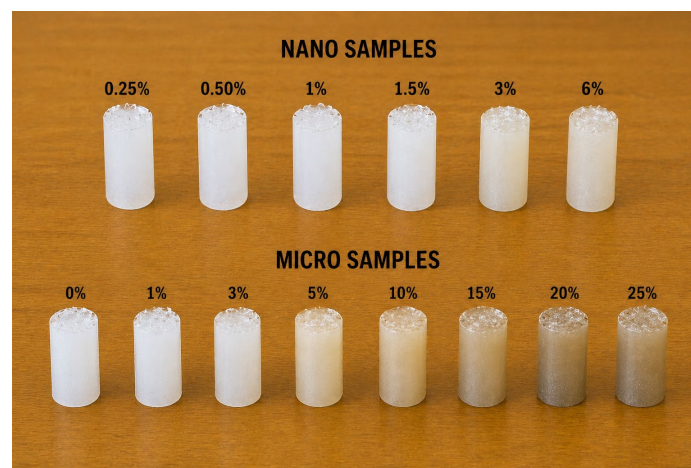


Figure 2. Comparison of Cylindrical PP Foams Prepared with Different Nano- and Micro-Silica Loadings

The resulting solid specimens were 6.5 mm in diameter and 13 mm high (Figure 2) and were used for compression testing according to ASTM D695 to determine the compressive modulus and strength of the composites.(American Society for Testing and Materials 2015).

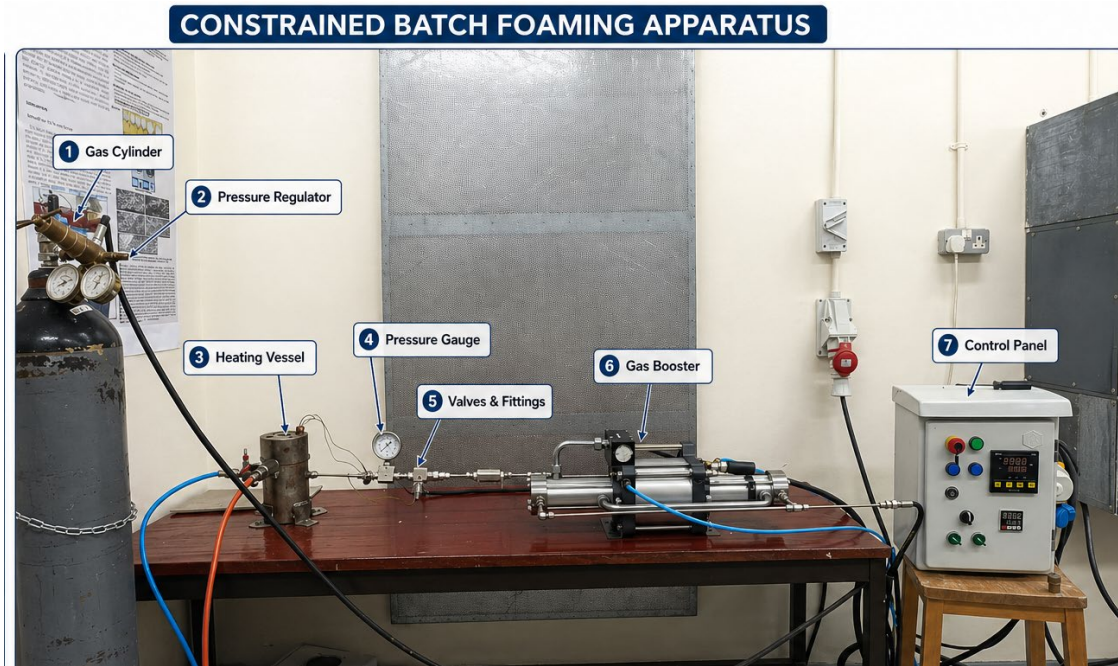


Figure 3. Experimental setup of the constrained batch foaming apparatus used for nitrogen (N_2) gas saturation and pressure-induced foaming of polypropylene composite samples under controlled temperature and pressure conditions.

For foaming, the solid samples were subjected to constrained batch foaming using nitrogen gas at 168°C and 5000 psi for 10 min (Figure 3). Rapid depressurization induced cell nucleation and growth, while the confined mold maintained the cylindrical geometry and prevented distortion. These processing parameters were optimized through preliminary trials to achieve stable and uniform foam structures.

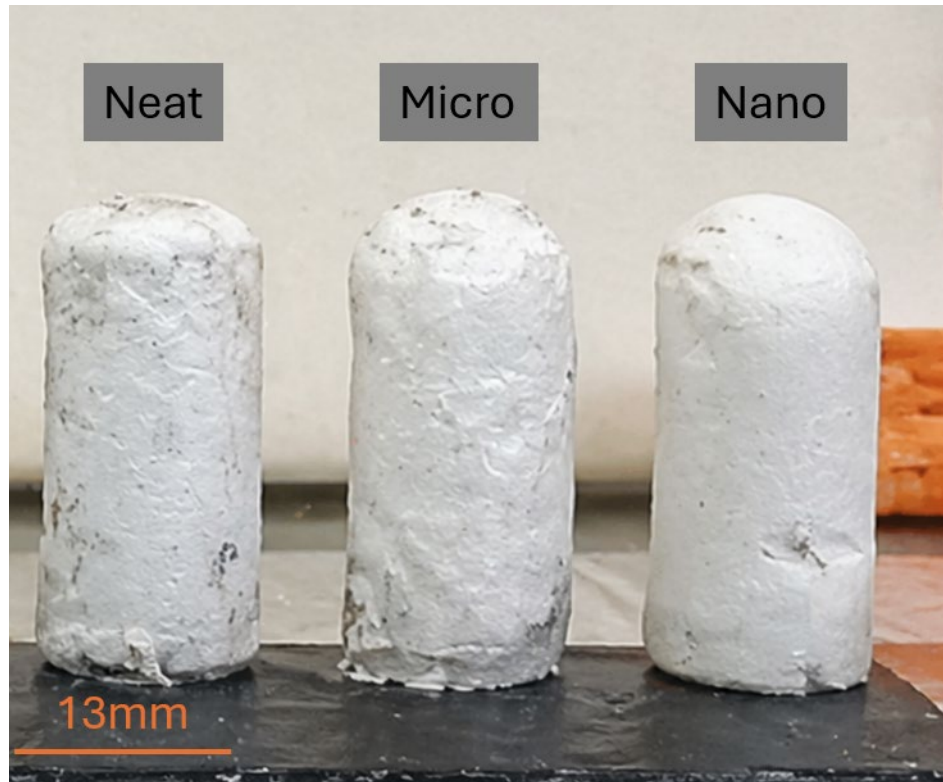


Figure 4. Comparison of Foamed PP Samples: Neat, Micro-Silica Reinforced, and Nano-Silica Reinforced

After foaming, the samples expanded to approximately 13 mm in diameter and 26 mm in height. Density was calculated from mass and dimensions, and the volume expansion ratio (VER) was determined as the ratio of foamed to solid volume. The cellular morphology of both solid and foamed samples was analyzed using scanning electron microscopy (SEM) to evaluate pore size, distribution, and cell wall thickness (Figure 4).

3. Results and Discussion

The mechanical performance of the solid (PP) composites reinforced with micro-silica was evaluated through compression testing, and the results are presented in Figure 5 and 6. The compression modulus, stress-strain behavior, and compressive strength at 10% strain were analyzed to determine the influence of filler loading on the stiffness and load-bearing response of the composites. Compression testing was performed using five replicate specimens for each formulation to ensure statistical reliability and reproducibility of the measured mechanical properties. The reported compressive modulus and strength values represent the average of the five specimens.

3.1 Mechanical Properties of Solid Samples Reinforced with Micro-Silica

According to Figure 5, compression modulus of neat PP was recorded at 679.39 MPa; when silica was added to create polymer composite, compression modulus continued to increase with increasing silica filler content, reaching an increased value of 1000 MPa for 10% filler content (47.19% improvement in compression modulus over neat PP). Increased compression modulus with addition of silica is primarily due to rigidity of silica particles which limit any deformation of polymer chains during compression. Well dispersed filler particles allow for better transfer of loads from matrix to reinforcing phase and thus improve composite's stiffness. On the other hand, for 15, 20, and 25 wt% filler amounts, compression modulus was 743 MPa, 607.67 MPa, and 490.67 MPa respectively, indicating a reduction in compression modulus past 10 wt%. One cause of decreasing compression modulus beyond 10 wt% filler content is agglomeration of silica particles, poor wetting of filler surfaces, and increased number of stress concentration sites created from excessive filler contents.

The compressive strength developed according to a similar trend to that produced at 10% strain (refer to Figure 5c). For the neat PP, the compressive strength was 39.99 MPa and this increased linearly with the increase in filler loading

to provide a peak strength of 52.75 MPa at 10 wt% silica. This increase confirms that micro-silica provided a reinforcing effect, where the rigid particles act as a barrier to localized plastic deformation and improve the resistance of the composite to compressive stress. Beyond the optimum loading level, the strength of the composite began to decline linearly to 50.59 MPa at 15 wt%, 48.25 MPa at 20 wt% and sharply to 27.54 MPa at 25 wt%. The sharp drop in strength observed at high particle loading levels suggests that the particles were poorly dispersed and therefore there was reduced continuity of the matrix, resulting in the composite's inability to carry compressive loads.

Figure 5b illustrates the stress-strain relationships for the composites studied. All of the samples showed a linear elastic behavior initially, this was subsequently followed by a gradual hardening of the material through an increase in stress with continued application of strain. The silica filled composites also demonstrated larger initial slopes in comparison to the neat PP indicating that the modulus of elasticity was higher for the silica filled composites. The 3 - 10% wt silica filled composites showed the best overall mechanical properties as a result of both increased stiffness and compressive strength compared to the 25% wt silica filled composites which had significantly lower stress at all levels of strain and appeared to have structurally failed early in the application of stress due to bond failure between the filler and matrix.



Figure 5. Mechanical properties of solid polypropylene/micro-silica composites: (a) compression modulus (E), (b) compressive stress–strain curves, and (c) compressive strength at 10% strain as a function of micro-silica content.

According to the results of the study from a materials engineering viewpoint, a maximum of 10 wt% micro-silica was determined to be the optimal filler content for maximizing particle reinforcement in conjunction with incremental levels of matrix continuity. A low level of filler resolve not provide adequate amounts of full reinforcement, while a high level of filler resolve result in the dominance of poor interfacial bonding and agglomeration. Therefore, to achieve improved mechanical properties, controlled silica loading is an important factor when developing PP composites that will be used for future foaming applications.

3.2 Mechanical Properties of Solid Samples Reinforced with Nano-Silica

The mechanical properties of the solid (PP) composites reinforced with nano-silica were evaluated by compression testing, and the results are presented in **Figure 6**. The effects of nano-silica loading on compression modulus, compressive strength at 10% strain, and stress–strain behavior were analyzed to determine the reinforcing efficiency of nanoscale silica particles within the PP matrix.

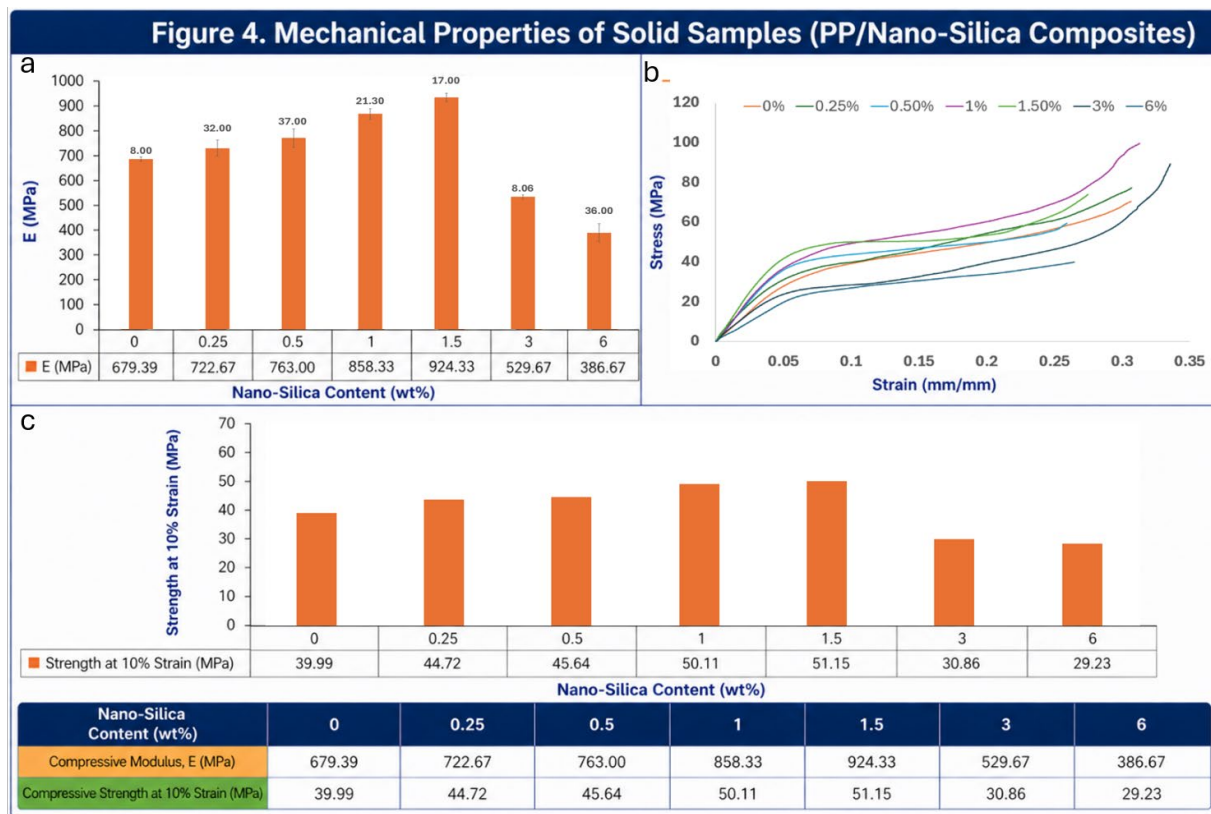


Figure 6. Mechanical properties of solid polypropylene/nano-silica composites: (a) compression modulus (E), (b) compressive stress–strain curves, and (c) compressive strength at 10% strain as a function of nano-silica content.

As shown in Figure 6a, neat PP exhibited a compression modulus of 679.39 MPa. The incorporation of nano-silica increased the modulus progressively to 722.67 MPa, 763.00 MPa, and 858.33 MPa at 0.25 wt%, 0.50 wt%, and 1 wt%, respectively. The highest modulus value of 924.33 MPa was obtained at 1.5 wt% nano-silica, representing an increase of approximately 36% relative to neat PP. This improvement is attributed to the high specific surface area of nanoparticles, which enhances interfacial interaction with the polymer matrix and improves stress transfer efficiency under compressive loading. In addition, the nanoparticles restrict chain mobility of PP, leading to increased stiffness.

At higher loadings, the modulus decreased sharply to 529.67 MPa at 3 wt% and further to 386.67 MPa at 6 wt%. This reduction is commonly associated with nanoparticle agglomeration caused by strong surface attraction between particles. Agglomerated clusters reduce the effective filler surface area, create stress concentration sites, and interrupt matrix continuity, thereby lowering the stiffness of the composite.

A similar trend was observed for compressive strength at 10% strain, as shown in Figure 6c. Neat PP recorded a strength of 39.99 MPa, which increased gradually with nano-silica loading to 44.72 MPa at 0.25 wt%, 45.64 MPa at 0.50 wt%, and 50.11 MPa at 1 wt%. The compressive strength was demonstrated with a peak of 51.15 MPa at 1.5 wt% indicating this amount gave the best performance between dispersion of the filler particles and reinforcement of the matrix. Higher loading of the filler increased compressive strength due to uniformly dispersed nano-silica acting like rigid reinforcements resisting localized plastic deformation and increasing load capacity of the composite. Conversely, 3 wt% saw a decrease in compressive strength down to a value of 30.86 MPa, and by 6 wt% it was decreased again down to 29.23 MPa.

The reduction in mechanical performance at higher nano-silica loadings is attributed to nanoparticle agglomeration, which reduces dispersion quality and creates stress concentration sites within the polymer matrix. These agglomerates act as structural defects that hinder efficient stress transfer and promote premature failure under compressive loading. Support for this data can be seen by comparing the stress strain curves shown in Figure 6b for the composites with 1

wt% and 1.5 wt% of nano-silica as they have steeper slopes at the beginning of the elastic phase than pure PP. In addition, they also had greater stress than pure PP through out the whole deformation process indicating higher modulus and greater resistance to deformation. On the other hand, lower stress responses and prior mechanical softening in the 3 wt% and 6 wt% samples show that at high levels of filler content, the filler's ability to reinforce the material is inefficient.

3.3 Foaming Performance of PP/Micro-Silica and PP/Nano-Silica Composites

SEM images were analyzed using ImageJ software. The images were calibrated using the scale bar, and cell diameter and wall thickness were measured from representative regions. The mean cell diameter was determined by averaging multiple cell measurements for each sample.

The SEM micrographs presented in Figure 7 illustrate the effect of silica particle size on the fracture morphology of (PP) composites. Neat PP (Figure 7a) has a smooth and continuous fracture morphology with the presence of layered features which is generally typical of ductile deformation. It can be seen that there are no fillers present; hence, the matrix is uniform, with very few defects, and therefore has an even stress distribution, but does not have much resistance to crack propagation.

The surface of the PP/micro-silica composite (refer to Fig 7b) is noticeably rougher and more heterogeneous than that of the PP/w-silica (compared to Fig 7c). Evidence of voids, particle pull-out, and tear defects indicative of a low bond strength at the interphase between the PP matrix and micro-sized silica particles are present on the surface of the composite.

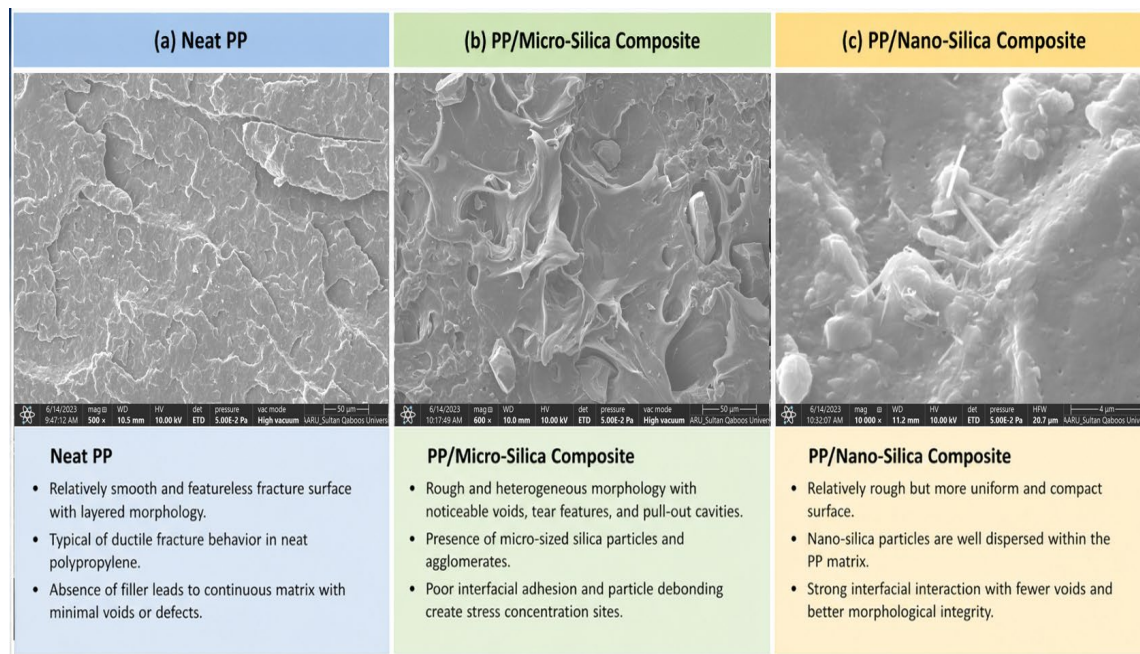


Figure 7. SEM Morphology and Foaming Behavior of Foamed PP/Micro-Silica and PP/Nano-Silica Composites.

The presence of agglomerates also forms localized stress concentration areas that could propagate cracks, resulting in lower mechanical efficiency. Therefore, micro-silica does not reinforce the matrix sufficiently due to the lack of effective bonding at the interface

3.4 SEM Morphology and Foaming Behavior of Foamed PP/Micro-Silica and PP/Nano-Silica Composites

Figure 8 illustrates the SEM micrographs of the foamed samples revealed clear differences in cellular morphology and foam quality depending on the silica type incorporated into the (PP) matrix. The neat PP foam exhibited a relatively irregular cellular structure with non-uniform pore distribution and comparatively large average cell diameter

(~322 μm). The cell walls were thicker (~10 μm), indicating limited nucleation density and unrestricted bubble growth during foaming. This behaviour is typical of unfilled PP, where the absence of heterogeneous nucleation sites results in fewer cells and coarser foam morphology.

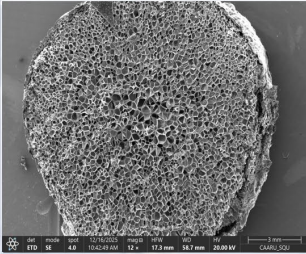
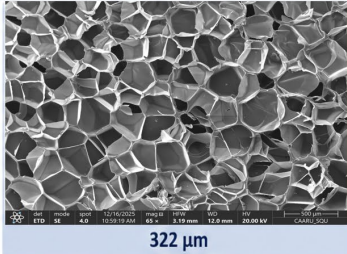
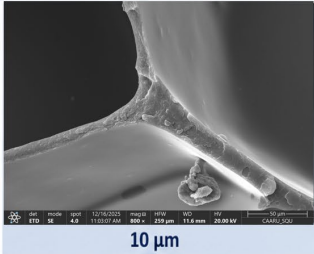
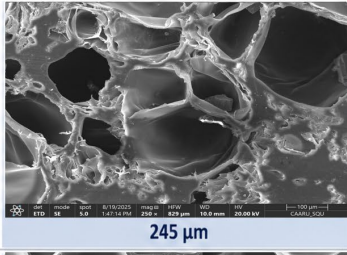
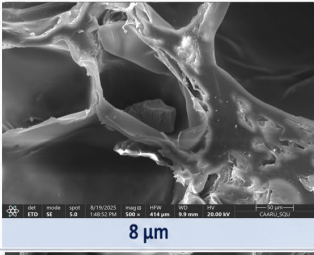
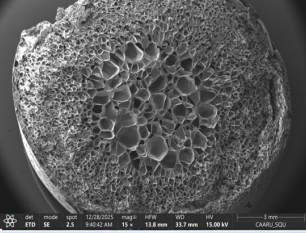
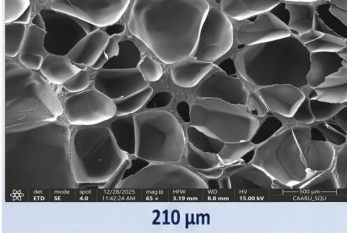
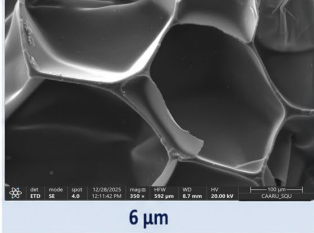
Table 3. SEM Morphology and Cellular Structure of Foamed PP Composites			
Sample	Overall View (Low Magnification)	Cell Structure / Middle Cell Diameter (High Magnification)	Cell Wall Thickness (High Magnification)
Neat PP		 322 μm	 10 μm
PP/Micro-Silica		 245 μm	 8 μm
PP/Nano-Silica		 210 μm	 6 μm

Figure 8. SEM Analysis of Cellular Morphology, Cell Size, and Wall Thickness of Foamed PP and Silica-Reinforced Composites

The PP/micro-silica composite provides a substantially more refined foam structure than that of neat PP, with average cell diameter reduced to roughly 245 μm and wall thickness to approximately 8 μm . Micro-sized silica contributes as a heterogeneous nucleation site for the enhancement of cell population density and controls excessive growth of the cells. However, the cellular structure is still partially irregular – it is common to observe areas with collapsed cells and/or areas where cells are open to each other in the SEM images of the samples. One possible reason for this is particle agglomeration, which leads to reduced adhesion at the interface between the particle and the matrix, resulting in high localised concentrations of stress and low melt strength during the expansion stage. The most uniformly and optimally foamed specimens were created from the combination of (PP) and nano-silica, with an average size of about 210 μm and the thickness of the cell walls measured at approximately 6 μm .

Cells were more spherical than any other sample and had a greater level of uniformity and stability. This improvement is mainly due to the very small size of the nano-silica particles along with their very high specific surface area, which allows for a much greater number of nucleation sites to form as well as provide a greater intermolecular attraction to the PP polymer matrix. All these factors act to promote homogeneous bubble nucleation, to reduce cell coalescence and to provide additional stability to cell walls during their growth process.

3.5 Density Reduction and Volumetric Expansion of Foamed PP Samples

In determining both the density and the foaming characteristics of (PP) prior to and after batch foaming under constrained conditions as shown in Table 3, it was found that there is a significant decrease in density ($0.765 \text{ g/cm}^3 - 0.096 \text{ g/cm}^3 = 0.669 \text{ g/cm}^3$) equating to 87.5% reduction in density, creating a very porous structure. The foaming efficiency achieved during the processing of PP was demonstrated by the successful formation of cellular morphology through nitrogen saturation and rapid depressurization. When the dimensions of the sample increased twice as high and twice as wide, the resulting volume from the expansion increased 8 times while its mass remained constant.

Table 3. Density, Dimensional Changes, and Expansion Ratios of PP Samples Before and After Constrained Batch Foaming

Parameter	Mass (g)	Height (mm)	Diameter (mm)	Volume (cm ³)	Density (g/cm ³)	Volume Expansion Ratio	Density Reduction (%)
Before Foaming (Solid Sample)	0.33	13	6.5	0.431	0.765	-	-
After Foaming (Foamed Sample)	0.33	26	13	3.451	0.096	8.0×	87.5%

6. Conclusion

The purpose of this research was to determine whether the incorporation of micro- and nano-silica would improve the mechanical behaviour, morphology and foaming characteristics of (PP) composite foams made using extrusion and batch foaming methods. The experimental findings yielded improvements to the mechanical properties of solid sheets of PP by adding silica to the composites; micro-silica produced the greatest benefit at about 10 wt% while nano-silica provided better improvements to the mechanical properties of PP at lower loadings (1 - 1.5 wt%) than by using micro-silica due to its greater surface area and improved compatibility with the (PP) matrix. Scanning electron micrographs show that the fracture surfaces of pure PP are very smooth and ductile, whereas those of the micro-silica composites have a very rough appearance (indicating the presence of voids) and that some of the micro-silica has removed itself from the polymer matrix (i.e., particle pull-out), indicating low interfacial bonding between the polymer and silica particles.

Conversely, the fracture surfaces of the nano-silica composites have a much more consistent and compact appearance than the micro-silica composites, thus confirming that the nano-silica was well dispersed within the polymer matrix and that load transfer between the polymer matrix and the nano-silica was enhanced. The cellular structure of constrained batch foams was highly affected by treating with silica fillers. It was found that when using neat PP, large irregular cellular structures were formed whereas micro-silica filled PP resulted in a smaller cell size and limited degree of nucleation. When using nano-silica, the foams produced were smaller and more uniform, proving to be the most effective agent to encourage uniform cell formation and maintain the stability of the foam structure. The foaming process caused the composite to lose 87.5% of its original density (0.765 g/cm^3 vs. 0.096 g/cm^3) and increase in volume approximately 8 times while keeping the cylindrical shape of the sample. The data indicates that nano-silica shows the greatest potential to improve the mechanical and foaming properties of PP composites, making this material an important consideration for developing environmentally sustainable methods to create lightweight materials suitable for advanced engineering applications

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Moosa Salim Moosa Al Kharusi is an accomplished engineer and academic, currently serving as an Assistant Professor at Sultan Qaboos University (SQU). He holds a Ph.D. in Mechanical Engineering from Sultan Qaboos University, where his research focused on the effective mechanical properties of carbon nanotube-based nanocomposites using computational mechanics. His academic journey also includes a Master's degree in modeling, simulation, and testing of water-swelling and oil-swelling elastomers. Dr. Moosa has a rich background in research and development, particularly in the oil and gas sector, where he has contributed to projects involving the performance evaluation of elastomer seals and the mechanical behavior of advanced materials. His work has been published in numerous prestigious journals and presented at international conferences.

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