

Plasma-Induced Surface Functionalization of Polymer Powders for Integration into UV-Resistant Functional Composites

Akram A. Al-Asadi^{1*}, Abdulrazzaq S Abdullah¹, Adnan A. Ateeq¹, Kadhim H. Hassan², Alaa Almansoori³

¹Chemical & Petrochemical Techniques Engineering Department, Basra Engineering Technical College, Southern Technical University, Basra, Iraq

²Electrical Engineering Techniques Department, Basra Engineering Technical College, Southern Technical University, Basra, Iraq

³Institute for Technical Physics and Materials Science, HUN-REN Centre for Energy Research, Budapest, Hungary

*Email: akramalasadi@stu.edu.iq

Article Info	Abstract
Received 10/08/2025	This study investigates the effects of plasma surface treatment on the thermal and morphological properties of polyamide 12 (PA12) powder. The powders were treated for 1 h and 2 h under full power in an air environment. Thermogravimetric analysis (TGA) results demonstrated that the plasma action improved the maximum decomposition temperature from 449.3 °C for the untreated polyamide 12 to 461.7 °C for the 2-h-treated sample, indicating improved thermal stability. The analysis of differential scanning calorimetry (DSC) revealed a marked increase in the temperature of crystallization (T _c) from 133.31 °C for the untreated PA12 sample to 141.7 °C for the 2-h sample, while the melting temperature is approximately constant at 185 °C. The SEM images demonstrated that plasma treatment resulted in a roughened, more homogeneous surface morphology with significantly fewer surface defects and irregularities. Plasma treatment enhanced the wettability and water dispersion of PA12, as plasma-treated powders showed fast spreading and stable suspension in water due to the introduction of polar groups and increased surface pores. The change from a water-hating grouping to a water-loving scattering provides a strong basis for water-based processing and future composite design that will need strong interfacial interactions. Thus, these results confirmed the importance of plasma treatment as an environmentally friendly method in tailoring the properties of PA12 for UV-resistant applications.
Revised 21/10/2026	
Accepted 23/10/2026	

Keywords: Crystallization, Differential Scanning Calorimetry (DSC), Morphology, Plasma treatment, Polyamide 12, Thermal stability, Thermogravimetric Analysis (TGA), Wettability.

1. Introduction

Polyamide 12 (PA12), nylon 12, is a semi-crystalline thermoplastic polymer renowned for its good mechanical properties, stability against some chemicals, and low moisture absorption compared to other polyamides [1], [2]. Hence, it is well suited for demanding applications in additive manufacturing, for example, laser sintering, owing to its excellent flowability and thermal processability to enable the production of complex and precise parts with strong, reliable mechanical properties [3], [4]. This places PA12 at the center of such important industries with material demand for light, strong parts including the automotive, aerospace and medical industries.

Because of PA12 semi-crystalline nature, it offers a good heat resistance to avoid the material deformation when cyclic thermal loading is applied [5], [2]. The inherent UV stability of PA12 makes it suitable for compounds for outdoor applications such as protective coatings and textiles exposed to sunlight and weather conditions [6], [7]. However, in the long term it can undergo chain scission and surface degradation, which weakens mechanical performance [8], [9]. The addition of short glass fibers, carbon nanotubes or metal oxides in the polymer is used to improve the thermal and UV resistance that not only improves the strength but also gives resistance in the environment, all the while maintaining good processability [10], [12]. Further to the optimized processing, the high

temperature annealing and the energy density control further enhance the applicability of PA12 for high performance applications [13], [14]; these results show the very high necessity of application-specific modifications in critical areas for widening the applicability of PA12.

Additive manufacturing, particularly laser sintering (LS) with PA12, is beneficial as it provides a homogeneous powder structure and controlled particle size, enabling the creation of parts with intricate geometries and mechanical properties [15], [16]. After careful optimization of the processing cycles for sustaining the application performance, the material exhibits change as isothermal and isomeric effects in the course of microstructural evolution [9], [17]. The material is compatible to fillers, e.g. the addition of glass beads or nanoclays to the material improves its applicability in electronics and automotive industries by enhancing both the thermal conductivity and the mechanical strength [18], [19].

However, environmentally friendly plasma treatment of PA12 is a good approach in comparison to reinforcement with nanofillers toward solving the problem of environmental resistance and aspect strength limitations for PA12 surface properties. Ionized gases modify surface chemistry and morphology, wettability, adhesion, and UV and thermal degradation resistance for PA12 without affecting bulk mechanical properties [20], [21]. Such techniques can produce polar groups, hydroxyl or carboxyl, and enhance the surface energy in coatings and adhesives [22], [23]. These changes find applications in additive manufacturing where surface properties such as roughness, adhesion, and interfacial properties are required [24], [25]. Plasma treatments are a type of low-temperature process that can make very good structural and UV improvements on the textile and film forms of PA12 while also improving surface functionality [26], [27]. The green nature of plasma treatment, avoiding harsh chemical agents, makes it suitable for sustainable manufacturing in the biomedical, electronic, and high-performance coating industries [28], [29]. By controlling the plasma parameters well, this technique optimizes the surface morphology and chemical functionality of PA12, enhancing its performance in demanding engineering contexts.

For these reasons, the present work focuses on plasma treatment to improve thermal stability and resistance to UV-induced breakdown of PA12 so that it can show strong potential for harsh-environment applications where mechanical performance and UV-resistance are required. Although many studies have been performed on plasma treatment of polymeric surfaces, relatively few studies have been carried out on powders, e.g. our previous works [30], [31]. This innovative study explores the plasma-induced surface modification approach to improve the thermal and photostability of PA12, achieve optimal integrity of microstructure and interlayer bonding in additive manufacturing and ultimately produce strong, thermal stability components suitable for cutting-edge application.

2. Experimental Methods

2.1. Materials

Polyamide 12 is a strictly semi crystalline thermoplastic polymer with the repeating unit (Fig. 1). Polyamide 12 is a key material in advanced manufacturing due to its superior mechanical properties, low moisture absorption and excellent processability [15], [32].

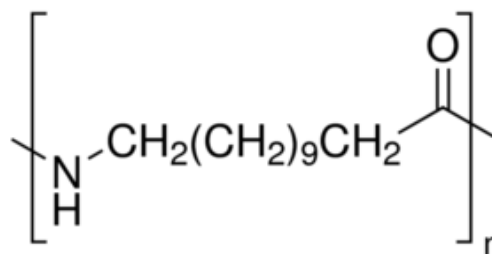


Figure 1. Chemical structure of Polyamide 12.

Unetched PA12 surfaces are compared to the natural surface of the material whereas 1 hour-etched surfaces are surfaces of the material colored with brown shades. After 2 hours, the surfaces have more pronounced brownish hues (see Fig. 2). These characteristics are the reason for the material to be regarded as one with the prowess for new engineering solutions.

2.2. Plasma Treatment Technique

Plasma treatment is an advanced surface treatment technique that uses ionized or activated gases to improve surface adhesion and wettability of P12, thereby making it more resistant to environmental stressors such as UV radiation and heat. The apparatus used for plasma treatment (Zepto from Diener Electronic, plasma-surface-technology, Germany, as indicated in Fig. 3) creates a high-energy plasma environment with the help of electrical discharge in a maintained gas atmosphere, for example, argon, nitrogen, or air. This then applies functional groups, like hydroxyl or carboxyl, to the PA12's surface [22], [33]. The procedure is well detailed in Fig. 4 and in our previous work. The plasma treatment operating parameters were set to a pressure of 0.3 mbar, max. power of 100 W, and a maximum duration of 1000 seconds using air as an operating gas. The plasma treatment was carried out on a similar quantity (5 grams) in Petri dishes of the same size for each patch to ensure consistent treatment conditions. PA12 powders were treated for 1 h and 2 h since these treatment durations were selected based on our previous work [30]. The procedure is well detailed in Fig. 4.

2.3. Testing and Examinations

2.3.1. Scanning electron microscopy (SEM)

Scanning Electron Microscopy (SEM) was used to characterize the surface morphology and microstructure of PA12 at high resolution, providing detailed images of PA12 powder morphology and particle size distribution, which are vital for ensuring consistent mechanical performance in processes like LS [30]. The images display surface characteristics such as particle shape and roughness, which are important for the processability and interlayer bonding of PA12 [24], [32]. SEM enables 3D imaging at high magnifications, which is useful for

optimizing manufacturing parameters of PA12, thus ensuring high-quality components for industries such as automotive, electronics.



Figure 2. Polyamide 12 surface color changes: natural (no etching), brown (1-hour etching), and darker brown (2-hour etching).

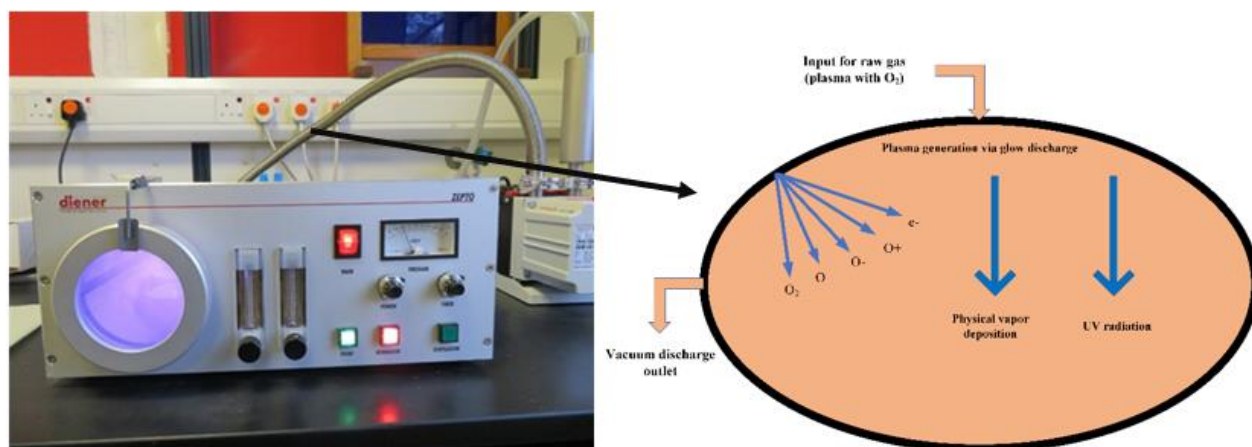


Figure 3. Plasma treatment apparatus.

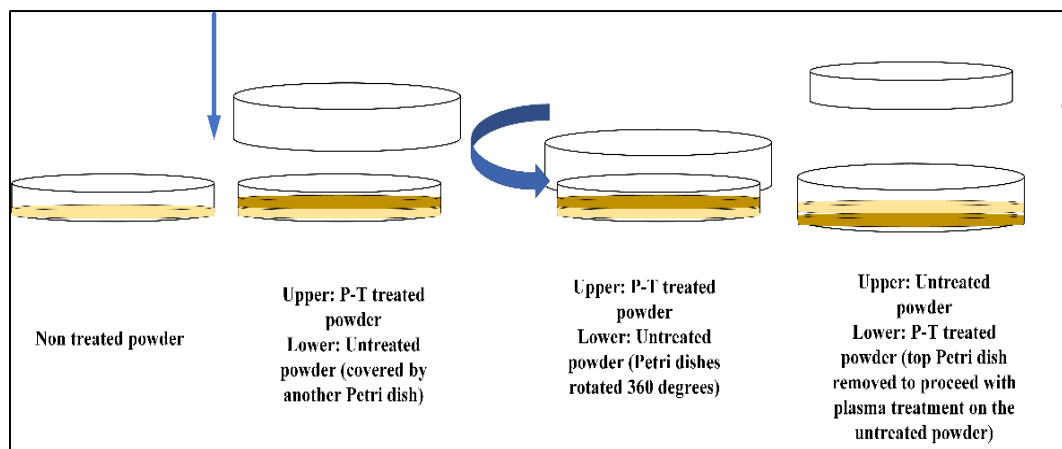


Figure 4. Diagram illustrating the plasma treatment (PT) procedure.

2.3.2. Thermogravimetric analysis (TGA)

Thermogravimetric Analysis (TGA) is an important thermal characterization method that is utilized to analyze the degradation behavior and thermal stability of PA12 under high temperature conditions common in additive manufacturing. The TGA device allows to measure the mass loss of the powder as a function of temperature in a controlled atmosphere and provides data on the thermal decomposition of PA12 and oxidative stability [10], [19]. This technique is important for understanding the aging mechanisms of PA12 during LS since thermal exposure can cause chain scission and microstructural changes that affect its durability. TGA also supports the strategies of recycling PA12 powders by quantifying the degree of thermal degradation of reused materials. By identifying temperature thresholds for weight loss, TGA aids in optimizing processing parameters to enhance PA12's thermal resilience for applications in automotive, aerospace, and industrial sectors.

2.3.3. Differential scanning calorimetry (DSC)

The DSC apparatus measures heat flow associated with phase changes, such as melting and crystallization, yielding precise data on PA12's melting point (around 175.0–180.0°C), temperature of glass transition, and crystallinity governing its mechanical behavior [34].

To quantitatively support the DSC analysis, the samples' crystallinities (X_c) were determined from the following [35]:

$$X_c = \frac{\Delta H_{\text{sample}}}{\Delta H_{100\%}} \times 100\% \quad (1)$$

where:

X_c = degree of crystallinity (%)

ΔH_{sample} = measured enthalpy of fusion for the sample (J/g)

$\Delta H_{100\%}$ = Enthalpy of fusion for 100% crystalline PA12, considered as 216 J/g [36]. It also supports the optimization of manufacturing processes to produce components with superior mechanical and thermal performance for the applications of aerospace, automotive, and biomedical [37].

2.3.4. Wettability and behaviour of treated samples

In order to examine the behaviour of the treated samples and water wettability, PA12 powders, untreated and treated for 1 hour in the plasma, were mixed separately with tap water to evaluate their interaction with water. The attained mixtures were softly stirred, and were monitored for 72 hours.

3. Results and Discussion

3.1. Thermogravimetric Analysis (TGA) of Plasma-Treated PA12

3.1.1. Sample without treatment (reference sample)

The thermogravimetric analysis (TGA) curve for untreated PA12 is shown in Fig. 5. The significant weight loss starts at 420.0°C, with a maximum thermal degradation temperature at 449.30°C and a corresponding weight loss of 49.81%. The sharp single decomposition step presents the thermal degradation of pure PA12 because the primary content is the

scission of the polymer backbone [33]. Residue above 600°C practically does not exist, showing no presence of thermally stable additives, which is characteristic of neat PA12.

3.1.2. One-hour plasma treatment for PA12

The plasma-treated PA12 sample displayed some improvement in thermal stability (See Fig. 5). The values were 421°C for the temperature at the weight lost onset, and 453.50°C for the extreme breakdown rate, with reduced weight loss of 45.20%. Higher decomposition temperature and reduced mass loss point to improved resistance against thermal degradation. Most of the energy is absorbed in modifying the surface chemistry of the polymer during the plasma treatment. Thus, energy is absorbed by the surface layers, leading to delayed decomposition by stabilizing the polymer chains at the surface [31].

3.1.3. Two-hour plasma treatment for PA12

Extending plasma treatment to two hours confirms even more marked thermal stability, as shown in Fig. 5. The weight loss beginning (onset) increases to 425°C, and the temperature at the maximum decomposition rate shifts to 461.70°C, with the maximum reduction or weight loss now at 32.64%.

3.1.4. Comparative analysis

Results in Table 1 show a continuous improvement in the thermal stability of PA12 as the plasma treatment time increases. The tendencies observed in the results are typical of the references where the improvement of the surface modification and quality interface leads to higher breakdown temperatures and lower mass or weight loss [38]. The observed enhanced thermal stability is quite useful for application needs in elevated temperatures such as automotive and aerospace components. The results are also in good agreement with the previous work and have well demonstrated the most important role of surface engineering and interface quality in enhancing the thermal properties of polymeric materials [38].

To summarize, TGA results show that the air plasma treatment is more efficient to improve the thermal stability of PA12, especially for longer exposure times. This was shown by lowering the onset of decomposition, increasing the maximum decomposition temperatures and reducing the total weight loss of the treated powder, thus confirming that plasma treatment is an efficient tool for optimizing the thermal performance of engineering polymers.

3.2. DSC Results

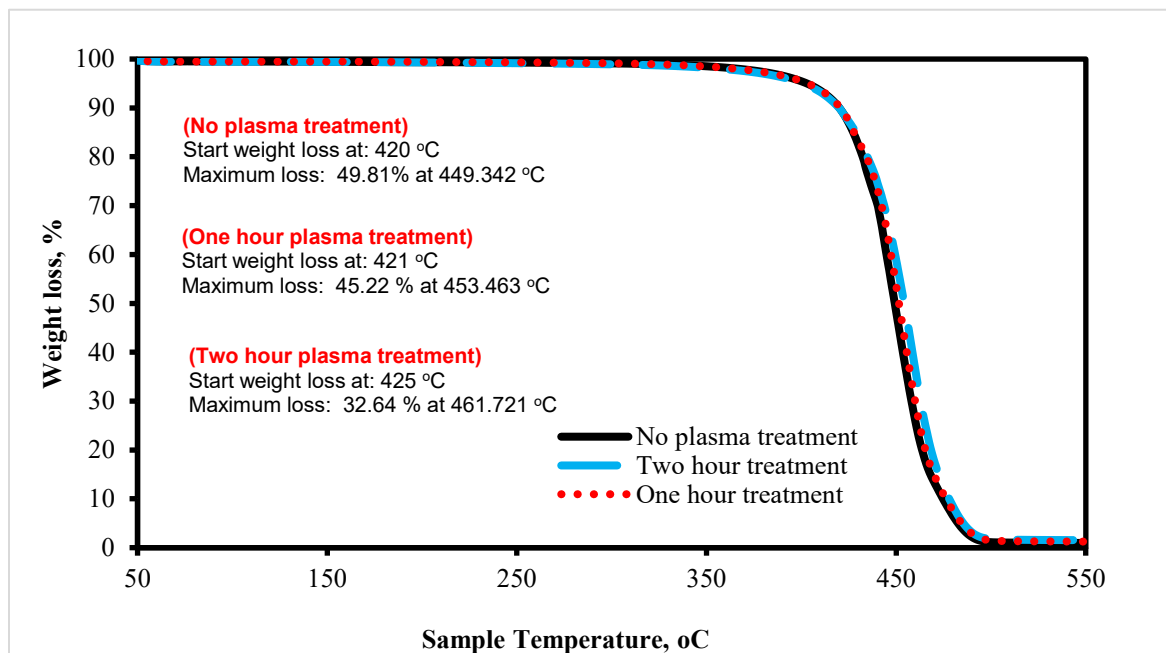
Table 2 presents the DSC results of untreated, 1 hr, and 2 hr plasma-treated PA12 powders. All obtained measurements were at of 30.0 °C/min cooling rate and 10 °C/min heating rate.

3.2.1. Melting temperature (T_m)

The melting temperature (T_m) was almost unchanged for any of the treatment durations by plasma; it was 185.52°C for the untreated sample (S_0) and 186.04°C for the sample plasma-treated for two hours (S_2). This unchanged T_m proves that the plasma treatment had no effect on the crystal structure of PA12 [39].

Table 1. Key TGA consequences of untreated and plasma-treated PA12 for one hour and two hours.

Sample	Onset of weight loss (°C)	Max. decomp. temp. (°C)	Max. weight loss (%)
Untreated PA12	420	449.3	49.81
1 hr plasma-treated PA12	421	453.5	45.22
2 hr plasma-treated PA12	425	461.7	32.64

**Figure 5.** TGA curve of untreated, one-hour plasma-treated, and two-hour plasma-treated PA12 powders.

3.2.2. Crystallization temperature (T_c)

The crystallization temperature (T_c) of the one-hour plasma-treated sample (S_1) increased dramatically over the untreated sample:

- Untreated PA12 (S_0): 133.31°C
- One-hour plasma treated (S_1): 139.67°C
- Two-hour plasma treated (S_2): 141.70°C

This shift of T_c towards a higher value implies that plasma treatment increases the nucleation activity, most probably due to the nucleating sites induced by polar functional groups and surface defects; during cooling, these sites become very strong in nature [38]. The fast plasma-induced kinetics of crystallization can save time on processing and better render dimensional stability concerning cooling.

3.2.3. Enthalpy of fusion (ΔH) and degree of crystallinity (X_c)

The enthalpy of fusion (ΔH) decreases with the increase in plasma treatment time, lowering the overall crystallinity.

- S_0 : 90.64J/g
- S_1 : 78.55J/g
- S_2 : 73.50J/g

Applied to each sample:

For S_0 : $X_c \approx 41.9\%$

For S_1 : $X_c \approx 36.7\%$

For S_2 : $X_c \approx 34.0\%$

A slight decrease in the degree of crystallinity was observed, indicating the restriction of crystal growth. The small decrease in crystallinity would not result in a decrease in stiffness but may increase toughness and impact resistance.

The DSC analysis reveals that plasma treatment slightly affects the crystalline behavior of PA12. As plasma treatment time is increased, higher crystallization temperatures are used with a slight decrease in crystallinity, while the melting temperature is kept constant.

3.3. Morphological Changes with Plasma Treatment

3.3.1. PA12 with no treatment

Fig. 6 (a) and (b) present SEM images of the untreated PA12 at different scales, showing a relatively roughened and homogeneous surface, more clearly visible in the lower magnification in Fig. 6 (a). The surface is dense with no visible defects or irregularities and, therefore, presents a morphology uniform to that of as-received PA12 powder. A study [30] reported similar observations of the untreated PA12 particles.

3.3.2. One-Hour Plasma-Treated PA12

SEM images of 1 hr plasma-treated PA12 sample indicated a considerable change in the surface characteristics of the powder particles, as shown in Fig. 7(a). Such morphological changes have often been demonstrated in the literature; that is, the accessibility of polymer surface reactivity is increased by

plasma exposure [30], [31]. However, at high magnifications, after plasma treatment, Microcracks and voids were clearly observed on the surface of treated particles (Fig. 7(b)). These pores, distributed all over the surface, are created as plasma

enhances etching as well as activation, thereby increasing surface area and providing new sites for potential interfacial interactions.

Table 2. DSC thermal properties of untreated and plasma-treated PA12 samples (1 and 2 hr durations).

Sample	Melting temp., T _m (°C)	Cooling temp., T _c (°C)	Heat of fusion, ΔH (J/g)
Untreated PA12 (S ₀)	185.52	133.31	90.64
1 hr plasma-treated (S ₁)	185.85	139.67	78.55
2 hr plasma-treated (S ₂)	186.04	141.70	73.50

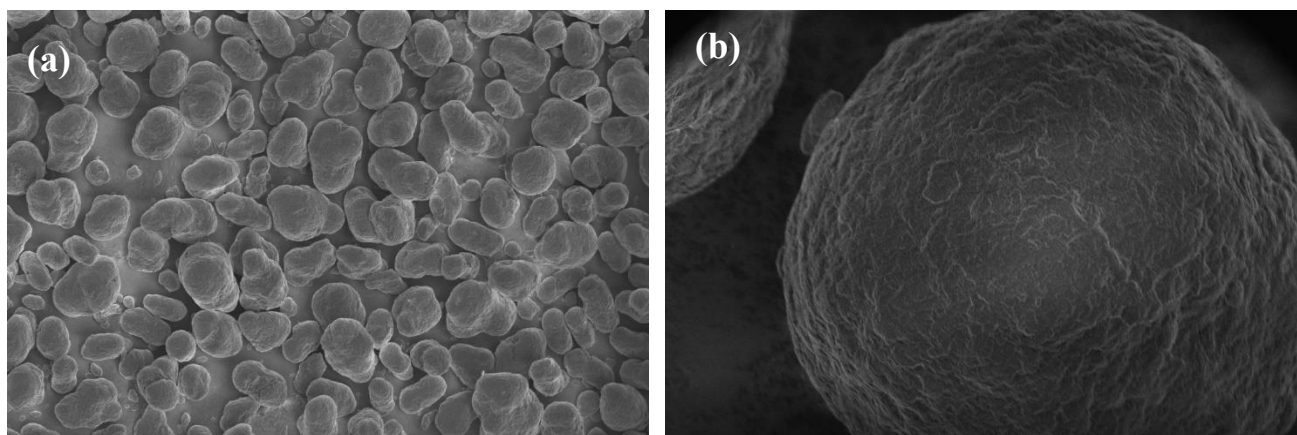


Figure 6. SEM images of untreated PA12 at (a) low magnification (300 μm) and (b) high magnification (20 μm)

The improved homogeneity coupled with porosity is beneficial; while the modified surface would enhance mechanical properties, the pores would act as nucleating sites for crystallinity and also assist the easy lodging of additives. Studies [30], [31] showed that plasma treatment of additives led to better dispersion and stronger interfacial adhesion in systems based on PA12.

3.3.3. Plasma treated PA12 for two hours

Two-hour plasma treatment results in more visible cracks and partially split particles, as observed in the low-magnification SEM image in Fig. 8 (a). At higher magnification (Fig. 8 (b)), the initiated cracks are much larger than those in the untreated samples and samples treated for one hour. This extensive porosity and cracking result from more intense plasma etching, which creates a highly activated surface for adsorbing many species. This kind of structure should boost interfacial adhesion and improve properties for later PA12-based nanocomposites. This has been supported by our previous works [30], [31].

Thus, SEM analysis showed the morphological evolution of PA12 with increasing plasma treatment time, wherein the dense, homogeneous, non-porous surface of the untreated sample becomes progressively roughened and more porous after 1 and 2 hours of plasma exposure. The surface homogeneity is greatly improved, and a trend of development of porosity is shown by the treatment. The two images in each panel favor (a) more surface homogeneity and (b) more porosity. These dual effects improve the intrinsic properties of PA12 and, at the same time, create a very good environment for the nanoclay and other additives to be well dispersed in the

polymer for applications requiring good thermal and photostability properties.

3.4. Water Wettability and Dispersion Behavior of Plasma-Treated PA12 Powders

3.4.1. Experimental observations

PA12 powders, both untreated and treated for 1 hour in the plasma, were mixed separately with tap water to evaluate their interaction with water. The obtained mixtures were gently stirred and monitored for 72 hours. Photos of the obtained mixtures were taken before stirring and after 1, 24, and 72 hours, as presented in Fig. 9. The results showed a dramatic difference in water wettability and dispersion behavior between the untreated and plasma-treated powders. Untreated PA12 aggregated and floated on the water surface, showing poor wettability and minimal dispersion, both before and after stirring. On the contrary, plasma-treated PA12 spread easily over the surface of water and penetrated, even before stirring. After stirring, the treated powder was well-dispersed, coloring the water, and eventually, within hours, its particles settled at the bottom of another container used for the experiment, while some floated and others remained suspended [30], [31].

3.4.2. Mechanisms of enhanced wettability

Introduction of (Oxygen-rich) Polar Functional Groups

This is achieved via plasma treatment, as the reactive plasma species react with the PA12 surface. Increasing surface functionalities increases surface energy and makes the surface hydrophilic; there is hydrogen bonding with water molecules,

which then allows easy wetting and dispersion (see Fig. 10) [40], [41].

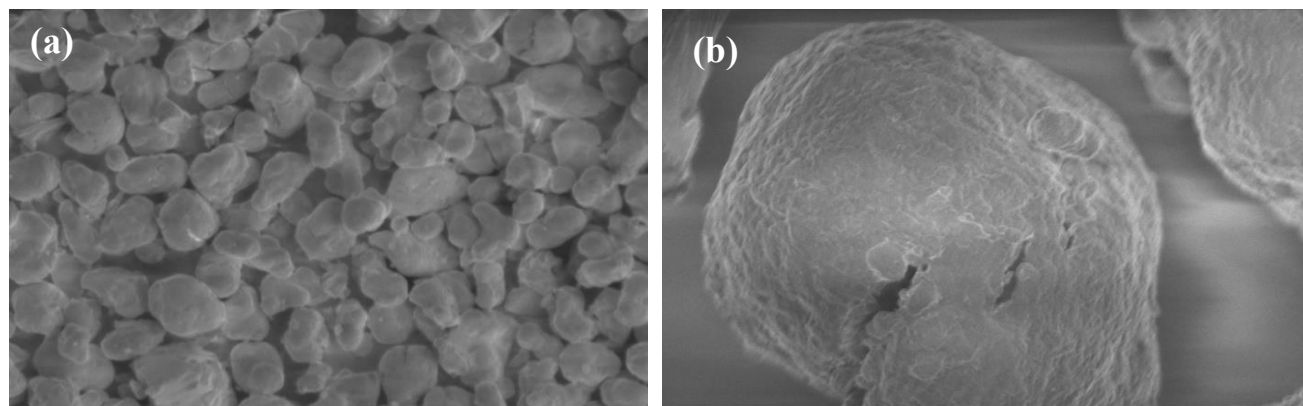


Figure 7. SEM images of one-hour plasma treated PA12 at scales of low (300 μm) and high (40 μm).

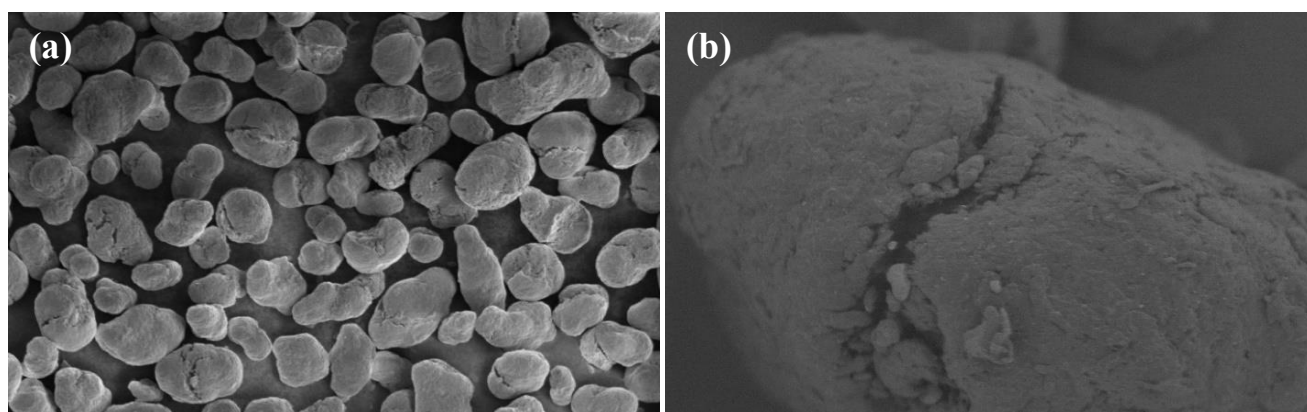


Figure 8. SEM images of two-hour plasma-treated PA12 at low (300 μm) and high (30 μm) magnifications.

Surface Cleaning and Activation

The plasma treatment removes surface contaminants and low-molecular-weight fragments, generating fresh reactive chains on the polymer surface and therefore increasing the effective surface area for water interaction. This allows water molecules to interact more easily with the polymer [41]. This leads to improved wettability and dispersion. Plasma treatment can etch the surface of PA12, creating nano- and micro-scale roughness and/or porosity dimensions, further increasing wettability since it provides more sites for water adhesion. The chemical etching, together with topographical changes, lowers the value of the water contact angle significantly; the powder becomes more hydrophilic, as shown in Fig. 10 [40], [42]. Untreated PA12 exhibits a rough, non-porous, and hydrophobic surface, resulting in poor interaction with water. Plasma treatment

introduces polar functional groups and surface porosity, transforming the surface to hydrophilic and enabling strong hydrogen bonding with water molecules.

Before Stirring: Plasma-treated PA12 disperses and starts to settle, whereas the untreated PA12 stays clustered at the top. The raised wettability and lowered surface tension of the treated powder let water wet and sink into the powder more easily [40].

During and after stirring, the treated powder results in a uniform dispersion that colors the water; it eventually settles, or maybe suspends, while the untreated powder forms a milky suspension that floats. The enhanced dispersion and settling is a direct result of improved water-polymer interactions due to increased density brought on by surface modification induced by the plasma [42].

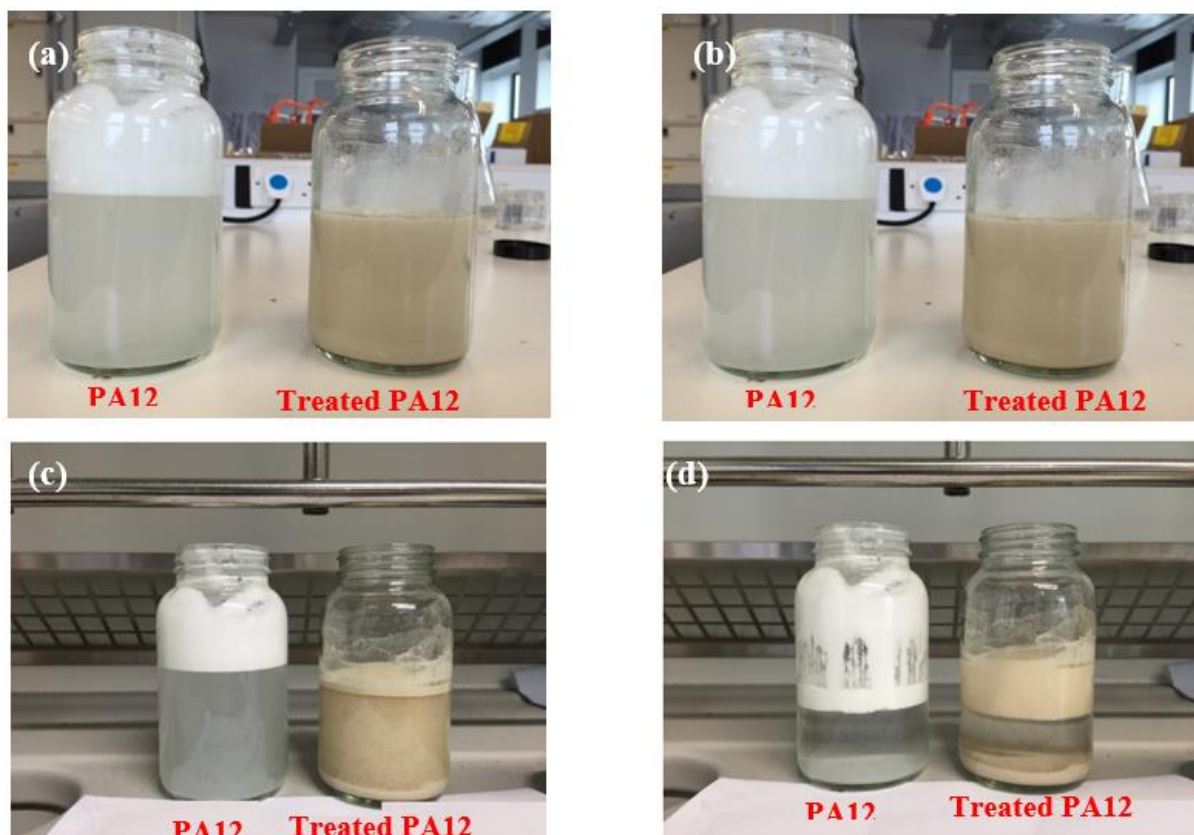


Figure 9. Dispersion behavior of untreated and treated PA12 in water (a) before stirring, (b) 1 hour after stirring, (c) 24 hours after stirring, and (d) 72 hours after stirring.

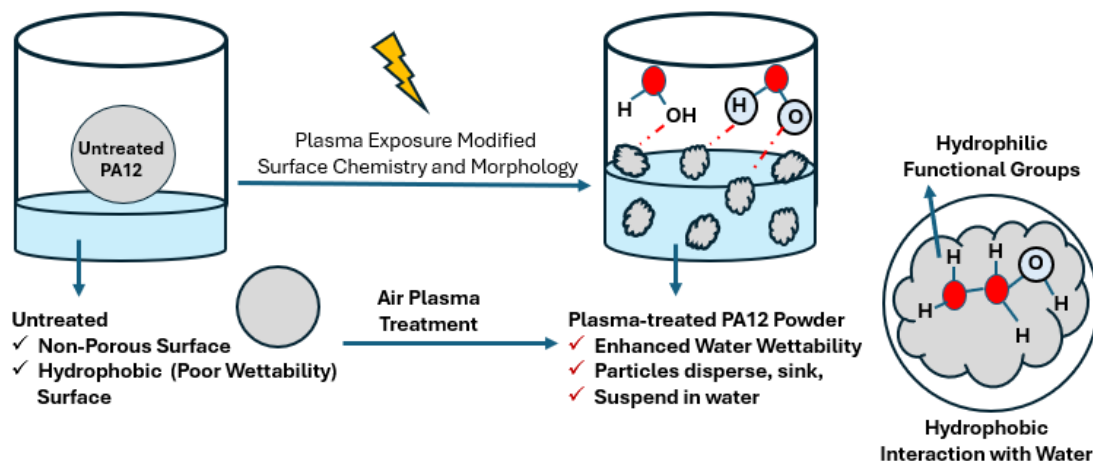


Figure 10. Schematic Illustration of Plasma-Induced Hydrophilicity Mechanism in PA12.

Long-Term Behavior (72 Hours): Plasma-treated powder exhibits a variety of behaviors (settling, floating, suspension), indicating strong and stable water interaction. Untreated powder mostly stays at the top, confirming persistent hydrophobicity [30], [31].

The role of plasma in increasing the wettability of polymers is already well described. It was shown by Almansoori et al. (2018) that the plasma treatment of PA12 powders imparts much superior wettability and dispersibility in water, probably due to the formation of polar functional groups and increased surface roughness [30], [31]. Primc et al. (2024) and Sant'Ana

et al. (2021) also report that plasma treatments on polyamide and water contact angles decreased prominently; the hydrophilicity increased due to surface oxidation as well as surface functionalization [41], [42]. Whereas studies like that of Mozetič (2020) say that a combination of oxygen-rich surface groups with increased roughness is a prerequisite for super-hydrophilic finishes in polymers [40]. Also, there was a report by Oliveira et al. (2017) that said plasma-treated polyamide fabrics show a big decrease in contact angle and improved water adsorption, which directly supports the findings of this study [43].

3.4.3. Implications for Future Composite Design

The improved wettability and porosity of plasma-treated PA12 powders would greatly benefit future composite development. The more hydrophilic surface and porosity make it easier to feed and disperse nanoclay and other additives, leading to better interfacial bonding and, hence, improved composite behavior [43]. These surface modifications offer an excellent opportunity for designing advanced PA12-based materials with properties suitable for the field of chemical engineering and renewable applications.

4. Conclusions

This study demonstrated that plasma surface treatment can be a very effective strategy for enhancing thermal stability and surface morphology of PA12 without additives.

The TGA results indicated that the sample treated with plasma has better thermal stability than the untreated ones. The obtained results demonstrated that the plasma treatment action raises the maximum decomposition temperature from 449.3 °C for the untreated PA12 to 461.7°C for the 2-hour treated sample, thereby indicating improved thermal stability. The latter would principally induce surface crosslinking and oxidation, leading to the former, which would later build up a barrier against heat as well as mass transfer. The DSC results revealed a quite meaningful increase in the crystallization temperature (T_c) from 133.3°C to 141.7°C for the 2-hour sample, while the melting temperature is approximately constant at 185 °C, accelerated nucleation due to surface defects induced by plasma, and polar functional groups. Simultaneously, the fusion enthalpy (ΔH) decreased to 90.64 J/g and 73.5 J/g, and the crystallinity was 41.9% for the sample treated by plasma, since it restricted the growth of large and perfect crystals.

SEM images of plasma-treated PA12 powder revealed a rough surface with heterogeneous pores and cracks compared to the untreated powder. The water wettability experiments indicated that the plasma treatment dramatically enhanced the hydrophilicity and dispersion behavior of PA12 powders in their aqueous environments. The plasma-treated PA12 wets rapidly, disperses readily, and remains stably suspended in water, as opposed to slow wetting and hydrophobic aggregation by the untreated powders. It is believed that the good hydric interaction is due to polar flexible groups at the surface and some kind of porosity development at the surface, which acts as an active site for hydrogen bonding with water molecules. This not only indicates the suitability of the plasma treatment for surface property adjustments but also suggests its use in achieving a uniform dispersion and strong interfacial adhesion in PA12-based composites, especially in hydrophilic nanoclay-containing composites.

Acknowledgements

This work was partially supported by Southern Technical University under scientific research awards, No. 9/7934, 10 Sep. 2025.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Author Contribution Statement

Akram A. Al-Asadi, Abdulrazzaq S. Abdullah, and Alaa Almansoori jointly wrote and discussed the results and discussion section. Alaa Almansoori proposed the research problem and developed the field experimental design. Adnan A. Ateeq and Kadhim H. Hassan contributed to data collection, analysis, and interpretation. All authors discussed the results, contributed to the preparation of the final manuscript, and approved the submitted version.

Use of LLM and AI

None declared.

Research funding

The authors received no external financial funding for the research, authorship, and publication of this article.

Data Availability

Not applicable.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Author Contribution Statement

Akram A. Al-Asadi, Abdulrazzaq S. Abdullah, and Alaa Almansoori jointly wrote and discussed the results and discussion section. Alaa Almansoori proposed the research problem and developed the field experimental design. Adnan A. Ateeq and Kadhim H. Hassan contributed to data collection, analysis, and interpretation. All authors discussed the results, contributed to the preparation of the final manuscript, and approved the submitted version.

Use of LLM and AI

None declared.

Research funding

The authors received no external financial funding for the research, authorship, and publication of this article.

Data Availability

Not applicable.

References

- [1] A. Touris, A. Turcios, E. Mintz, S. R. Pulugurtha, P. Thor, M. Jolly, and U. Jalgaonkar, "Effect of molecular weight and hydration on the tensile properties of polyamide 12," *Results in Materials*, vol. 8, Art. no. 100149, 2020. doi: <https://doi.org/10.1016/j.rinma.2020.100149>.
- [2] N. Ma, W. Liu, L. Ma, S. He, H. Liu, Z. Zhang, A. Sun, M. Huang, and C. Zhu, "Crystal transition and thermal behavior of Nylon 12," *e-Polymers*, vol. 20, no. 1, pp. 346–352, 2020. doi: <https://doi.org/10.1515/epoly-2020-0039>.
- [3] C. Cai, W. S. Tey, J. Chen, W. Zhu, X. Liu, T. Liu, L. Zhao, and K. Zhou, "Comparative study on 3D printing of polyamide 12 by selective laser sintering and multi jet fusion," *Journal of Materials Processing Technology*, vol. 288, Art. no. 116882, 2021. doi: <https://doi.org/10.1016/j.jmatprotec.2020.116882>.

- [4] S. Rosso, R. Meneghello, L. Biasetto, L. Grigolato, G. Concheri, and G. Savio, "In-depth comparison of polyamide 12 parts manufactured by Multi Jet Fusion and Selective Laser Sintering," *Additive Manufacturing*, vol. 36, Art. no. 101713, 2020. doi: <https://doi.org/10.1016/j.addma.2020.101713>.
- [5] A. J. Cano, A. Salazar, and J. Rodríguez, "Effect of temperature on the fracture behavior of polyamide 12 and glass-filled polyamide 12 processed by selective laser sintering," *Engineering Fracture Mechanics*, vol. 203, pp. 66–80, 2018. doi: <https://doi.org/10.1016/j.engfracmech.2018.07.035>.
- [6] Y. C. Ching, T. U. Gunathilake, K. Y. Ching, C. H. Chuah, V. Sandu, R. Singh, and N. S. Liou, "Effects of high temperature and ultraviolet radiation on polymer composites," in *Durability and Life Prediction in Biocomposites, Fibre-Reinforced Composites and Hybrid Composites*, Duxford, U.K.: Woodhead Publishing, 2019, pp. 407–426. doi: <https://doi.org/10.1016/B978-0-08-102290-0.00018-0>.
- [7] T. Puttonen, M. Salmi, and J. Partanen, "Mechanical properties and fracture characterization of additive manufacturing polyamide 12 after accelerated weathering," *Polymer Testing*, vol. 104, Art. no. 107376, 2021. doi: <https://doi.org/10.1016/j.polymertesting.2021.107376>.
- [8] N. D. Wanasekara, V. Chalivendra, and P. Calvert, "Effect of accelerated ultraviolet and thermal exposure on nanoscale mechanical properties of nylon fibers," *Polymer Engineering & Science*, vol. 52, no. 11, pp. 2482–2488, 2012. doi: <https://doi.org/10.1002/pen.23204>.
- [9] T. Stiller, E. Truszkiewicz, T. Schrank, B. Haar, G. Meier, W. Kraschitzer, G. Pinter, J. Lackner, and M. Berer, "Polyamide 12 powder ageing in laser beam-based powder bed fusion and its combined effects on powder and component characteristics," *Rapid Prototyping Journal*, vol. 31, no. 11, pp. 82–96, 2025. <https://doi.org/10.1108/RPJ-08-2024-0351>.
- [10] L. Lanzl, K. Wudy, and D. Drummer, "The effect of short glass fibers on the process behavior of polyamide 12 during selective laser beam melting," *Polymer Testing*, vol. 83, Art. no. 106313, 2020. doi: <https://doi.org/10.1016/j.polymertesting.2019.106313>.
- [11] S. Roy, T. Das, L. Zhang, Y. Li, Y. Ming, S. Ting, and C. Y. Yue, "Triggering compatibility and dispersion by selective plasma-functionalized carbon nanotubes to fabricate tough and enhanced Nylon 12 composites," *Polymer*, vol. 58, pp. 153–161, 2015. doi: <https://doi.org/10.1016/j.polymer.2014.12.032>.
- [12] P. Latko-Duralek, J. Rzepołuch, M. Staniszevska, K. Rosloniec, M. Bil, R. Kozera, and A. Boczkowska, "The antifungal fibers of polyamide 12 containing silver and metal oxides," *Materials*, vol. 16, no. 17, Art. no. 5837, 2023. doi: <https://doi.org/10.3390/ma16175837>.
- [13] X. Liu, W. S. Tey, J. Y. C. Choo, J. Chen, P. Tan, C. Cai, and K. Zhou, "Enhancing the mechanical strength of Multi Jet Fusion-printed polyamide 12 and its glass fiber-reinforced composite via high-temperature annealing," *Additive Manufacturing*, vol. 46, Art. no. 102205, 2021. doi: <https://doi.org/10.1016/j.addma.2021.102205>.
- [14] M. Pavan, M. Faes, D. Strobbe, B. Van Hooreweder, T. Craeghs, D. Moens, and W. Dewulf, "On the influence of inter-layer time and energy density on selected critical-to-quality properties of PA12 parts produced via laser sintering," *Polymer Testing*, vol. 61, pp. 386–395, 2017. doi: <https://doi.org/10.1016/j.polymertesting.2017.05.027>.
- [15] G. Wang, P. Wang, Z. Zhen, W. Zhang, and J. Ji, "Preparation of PA12 microspheres with tunable morphology and size for use in SLS processing," *Materials & Design*, vol. 87, pp. 656–662, Dec. 2015. doi: <https://doi.org/10.1016/j.matdes.2015.08.083>.
- [16] S. Josupeit, L. Ordia, and H.-J. Schmid, "Modelling of temperatures and heat flow within laser sintered part cakes," *Additive Manufacturing*, vol. 12, pp. 189–196, 2016. doi: <https://doi.org/10.1016/j.addma.2016.06.002>.
- [17] P. Chen, M. Tang, W. Zhu, L. Yang, S. Wen, C. Yan, H. Nan, and Y. Shi, "Systematical mechanism of polyamide-12 aging and its micro-structural evolution during laser sintering," *Polymer Testing*, vol. 67, pp. 370–379, 2018. doi: <https://doi.org/10.1016/j.polymertesting.2018.03.035>.
- [18] H. J. O'Connor and D. P. Dowling, "Comparison between the properties of polyamide 12 and glass-bead filled polyamide 12 using the Multi Jet Fusion printing process," *Additive Manufacturing*, vol. 31, Art. no. 100961, Jan. 2020. doi: <https://doi.org/10.1016/j.addma.2019.100961>.
- [19] L. Lanzl, K. Wudy, S. Greiner, and D. Drummer, "Selective laser sintering of copper-filled polyamide 12: Characterization of powder properties and process behavior," *Polymer Composites*, vol. 40, no. 5, pp. 1801–1809, 2019. doi: <https://doi.org/10.1002/pc.24940>.
- [20] G. Prime, "Surface modification of polyamides by gaseous plasma—Review and scientific challenges," *Polymers*, vol. 12, no. 12, Art. no. 3020, 2020. doi: <https://doi.org/10.3390/polym12123020>.
- [21] M. Bahrami, D. Lavayen-Farfan, M. A. Martínez, and J. Abenojar, "Experimental and numerical studies of polyamide 11 and 12 surfaces modified by atmospheric pressure plasma treatment," *Surfaces and Interfaces*, vol. 32, Art. no. 102154, 2022. doi: <https://doi.org/10.1016/j.surfin.2022.102154>.
- [22] J. Hnilica, L. Potočnáková, M. Stupavská, and V. Kudrle, "Rapid surface treatment of polyamide 12 by microwave plasma jet," *Applied Surface Science*, vol. 288, pp. 251–257, 2014. doi: <https://doi.org/10.1016/j.apsusc.2013.10.016>.
- [23] D. Pappas, A. Bujanda, J. D. Demaree, J. K. Hirvonen, W. Kosik, R. Jensen, and S. McKnight, "Surface modification of polyamide fibers and films using atmospheric plasmas," *Surface and Coatings Technology*, vol. 201, no. 7, pp. 4384–4388, 2006. doi: <https://doi.org/10.1016/j.surfcoat.2006.08.068>.
- [24] S. Petzold, J. Klett, A. Schauer, and T. A. Osswald, "Surface roughness of polyamide 12 parts manufactured using selective laser sintering," *Polymer Testing*, vol. 80, Art. no. 106094, 2019. doi: <https://doi.org/10.1016/j.polymertesting.2019.106094>.
- [25] D. Verdi, D. Merino-Millán, and A. Salazar, "Metallisation of additive manufactured polyamide 12 by low pressure cold spray," *Surface and Coatings Technology*, vol. 479, Art. no. 130484, 2024. doi: <https://doi.org/10.1016/j.surfcoat.2024.130484>.
- [26] J. Yip, K. Chan, K. M. Sin, and K. S. Lau, "Low temperature plasma-treated nylon fabrics," *Journal of Materials Processing Technology*, vol. 123, no. 1, pp. 5–12, 2002. doi: [https://doi.org/10.1016/S0924-0136\(02\)00024-9](https://doi.org/10.1016/S0924-0136(02)00024-9).
- [27] R. A. Jelil, "A review of low-temperature plasma treatment of textile materials," *Journal of Materials Science*, vol. 50, no. 18, pp. 5913–5943, 2015. <https://doi.org/10.1007/s10853-015-9152-4>.
- [28] A. A. Tyuftin and J. P. Kerry, "Review of surface treatment methods for polyamide films for potential application as smart packaging materials: Surface structure, antimicrobial and spectral properties," *Food Packaging and Shelf Life*, vol. 24, Art. no. 100475, 2020. doi: <https://doi.org/10.1016/j.fpsl.2020.100475>.
- [29] C. Che, B. Dashtbozorg, S. Qi, M. J. North, X. Li, H. Dong, and M. J. Jenkins, "The ageing of μ Plasma-modified polymers: The role of hydrophilicity," *Materials*, vol. 17, no. 6, Art. no. 1402, 2024. doi: <https://doi.org/10.3390/ma17061402>.
- [30] A. Almansoori, R. Seabright, C. Majewski, and C. Rodenburg, "Feasibility of plasma treated clay in clay/polymer nanocomposites powders for use Laser Sintering (LS)," *IOP Conference Series: Materials Science and Engineering*, vol. 195, no. 1, Art. no. 012003, 2017. doi: <https://doi.org/10.1088/1757-899X/195/1/012003>.
- [31] A. Almansoori and W. Alkaron, "Effect of low-pressure plasma treatment on the thermal behaviour of organo-modified montmorillonite nanoclay," *Archives of Materials Science and Engineering*, vol. 125, no. 1, pp. 5–14, 2024. doi: <https://doi.org/10.5604/01.3001.0054.4729>.
- [32] T. Stichel, T. Frick, T. Laumer, F. Tenner, T. Hausotte, M. Merklein, and M. Schmidt, "A round robin study for selective laser sintering of polyamide 12: Microstructural origin of the mechanical properties," *Optics & Laser Technology*, vol. 89, pp. 31–40, 2017. doi: <https://doi.org/10.1016/j.optlastec.2016.09.042>.
- [33] W. Zhang, L. Johnson, S. R. P. Silva, and M. K. Lei, "The effect of plasma modification on the sheet resistance of nylon fabrics coated with carbon nanotubes," *Applied Surface Science*, vol. 258, no. 20, pp. 8209–8213, 2012. doi: <https://doi.org/10.1016/j.apsusc.2012.05.023>.
- [34] H. W. B. Teo, T. Van Thai, C. Tang, K. Chen, J. Zeng, and H. Du, "Effects of additives and pre-heating temperature on interlayer shrinkage of

- polyamide-12 parts in Additive Manufacturing,” *Polymer*, vol. 327, Art. no. 128409, 2025. doi: <https://doi.org/10.1016/j.polymer.2025.128409>
- [35] D. W. van Krevelen and K. te Nijenhuis, *Properties of Polymers: Their Correlation with Chemical Structure; Their Numerical Estimation and Prediction from Additive Group Contributions*, 4th ed. Amsterdam, The Netherlands: Elsevier, 2009. doi: <https://doi.org/10.1016/C2009-0-05459-2>.
- [36] M. Arioli, L. Franco, and J. Puiggali, “Non-isothermal crystallization and thermal degradation studies on nylons 7,10 and 10,7 as isomeric odd-even and even-odd polyamides,” *Thermochimica Acta*, vol. 735, Art. no. 179721, 2024. doi: <https://doi.org/10.1016/j.tca.2024.179721>.
- [37] M. Kohutiar, L. Kakošová, M. Krbata, R. Janík, J. J. Fekiač, A. Brezničká, M. Eckert, P. Mikuš, and L. Timárová, “Comprehensive review: Technological approaches, properties, and applications of pure and reinforced polyamide 6 (PA6) and polyamide 12 (PA12) composite materials,” *Polymers*, vol. 17, no. 4, 442, 2025. doi: <https://doi.org/10.3390/polym17040442>.
- [38] J.-J. Luo and I. M. Daniel, “Characterization and modeling of mechanical behavior of polymer/clay nanocomposites,” *Composites Science and Technology*, vol. 63, no. 11, pp. 1607–1616, 2003. doi: [https://doi.org/10.1016/S0266-3538\(03\)00060-5](https://doi.org/10.1016/S0266-3538(03)00060-5).
- [39] S. Gul, A. Kausar, B. Muhammad, and S. Jabeen, “Research progress on properties and applications of polymer/clay nanocomposite,” *Polymer-Plastics Technology and Engineering*, vol. 55, no. 7, pp. 684–703, 2016. doi: <https://doi.org/10.1080/03602559.2015.1098699>.
- [40] M. Mozetič, “Plasma-stimulated super-hydrophilic surface finish of polymers,” *Polymers*, vol. 12, no. 11, 2498, 2020. doi: <https://doi.org/10.3390/polym12112498>.
- [41] P. L. Sant’Ana, J. R. Bortoleto, and S. F. Durrant, “Contact angle and wettability of commercial polymers after plasma treatment,” *London Journal of Engineering Research*, vol. 22, no. 7, pp. 13–33, 2022. [Online]. Available: <https://journalspress.com/contact-angle-and-wettability-of-commercial-polymers-studies-after-treatment/>.
- [42] G. Prime and M. Mozetič, “Surface modification of polymers by plasma treatment for appropriate adhesion of coatings,” *Materials*, vol. 17, no. 7, 1494, 2024. doi: <https://doi.org/10.3390/ma17071494>.
- [43] F. R. Oliveira, F. Steffens, P. S. B. de Holanda, J. H. O. do Nascimento, K. N. Matsui, and A. P. Souto, “Physical, chemical and morphological characterization of polyamide fabrics treated with plasma discharge,” *Materials Research*, vol. 20, Suppl. 2, pp. 60–68, 2017. doi: <https://doi.org/10.1590/1980-5373-MR-2016-1032>.