



# High-Performance HDPE/PP Composite Pipes: Morphological, Mechanical, and Antibacterial Insights

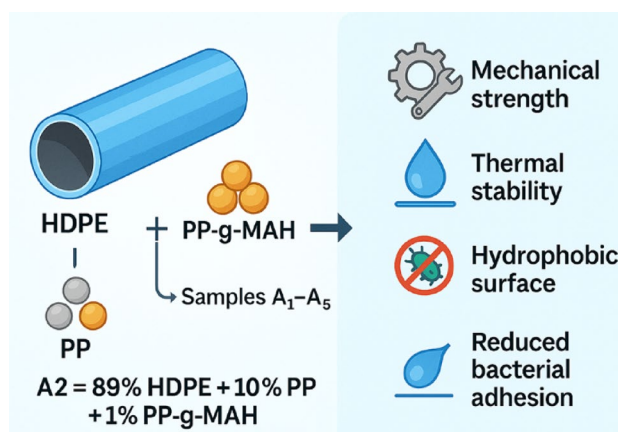
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## Abstract

This study developed compatible polymer composites based on a blend of high-density polyethylene (HDPE) and polypropylene (PP), modified with 1% maleic-anhydride-grafted polypropylene (PP-g-MAH) as a compatibilizer. Five formulations were prepared with HDPE/PP ratios of 100/0, 94/6, 89/11, 84/16, and 79/21, each containing 1 wt% (1% by weight) PP-g-MAH. The blends were comprehensively evaluated through morphological, mechanical, thermal, wettability, and bacteriological analyses to determine their suitability for sanitary water-pipe applications. Among all formulations, composite A2 (89% HDPE/10% PP/1% PP-g-MAH) demonstrated the most balanced and superior performance. It achieved a hardness of approximately 70 Shore D and an impact resistance close to 3.3 kJ/m<sup>2</sup>, while exhibiting enhanced thermal stability with a decomposition onset near 440 °C. Surface characterization revealed a smooth, homogeneous morphology and increased hydrophobicity, which contributed directly to its improved antibacterial behavior. Notably, A2 showed nearly a 30% reduction in *E. coli* adhesion compared to the control sample A0, confirming its hygienic advantages in potable-water environments. Overall, the synergistic effect of optimized polymer ratios and effective compatibilization produced a composite with high rigidity, excellent toughness, low thermal expansion, and reduced biofilm formation. These combined properties establish A2 as a highly promising and practical material for the fabrication of durable, thermally stable, and hygienically safe drinking water distribution pipes.

## Graphical abstract



**Keywords** HDPE · PP · Hardness · Impact strength · Antibacterial · TMA · TGA · DSC

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## Introduction

The demand for advanced polymeric materials that combine antimicrobial efficacy with robust mechanical performance is increasingly critical, particularly for ensuring the safety and longevity of drinking water distribution systems [1–3]. High-density polyethylene (HDPE) is widely employed in water pipe manufacturing due to its excellent flexibility, chemical resistance, and processability. However, a significant limitation of HDPE is its susceptibility to biofilm formation in humid environments, a consequence of its inherent surface characteristics [4, 5]. To address this issue, polypropylene (PP) can be blended with HDPE. The incorporation of anhydride-grafted polypropylene (PP-g-MAH) as a compatibilizer is a key strategy to enhance the adhesion and homogeneity between these otherwise immiscible polymers, thereby improving the overall material performance [6, 7]. The creation of a stable and homogeneous polymer blend is essential for achieving superior mechanical and thermal properties distinct from those of the individual components [8–10].

The engineering of polymers allows for precise control over their chemical and physical properties through various methods, including copolymerization, cross-linking, or the addition of fillers and compatibilizers [11, 12]. Polymer blends, which are mixtures of two or more polymers, represent a common approach to developing new materials with tailored characteristics [13]. The properties of these blends are highly dependent on the compatibility between the constituent polymers, which often requires a compatibilizing agent to achieve a stable morphology [14]. A prevalent method for producing such thermoplastic blends is melt mixing, which utilizes elevated temperatures to soften the polymers for uniform dispersion of components [15]. Surface properties, particularly wettability, are vital for applications like water pipes. Wettability is quantified by the contact angle, where a higher angle ( $>90^\circ$ ) indicates a hydrophobic surface that resists wetting; a desirable trait for inhibiting microbial adhesion [16, 17]. The integration of multiple materials into a composite result in entirely new chemical, thermal, and mechanical properties [18, 19].

The formation of bacterial films on polymer water pipes presents a persistent challenge, leading to reduced water quality and shorter pipe lifespan [20]. Despite the widespread use of HDPE, its limited resistance to bacterial adhesion and poor structural compatibility when blended with other polymers necessitate the development of improved formulations that offer better mechanical and thermal performance while minimizing bacterial growth. This has led to the need for a systematic study evaluating different mixing ratios and identifying the optimal formulation for sanitary applications.

PP-g-MAH was selected as one of the most effective compatibility agents in HDPE/PP blends due to its proven ability to improve interphase adhesion and reduce phase segregation at contact points. Specific HDPE/PP blend ratios within the range of 5%–20% were adopted to investigate the effect of progressively increasing PP content on surface structure, mechanical properties, thermal stability, and bacterial behavior. This approach is essential for determining the optimal ratio that provides a balance between durability and bacterial resistance in drinking water pipe applications [21, 22].

In this study, we investigate the thermomechanical properties and antibacterial efficacy of HDPE/PP blends compatibilized with 1% PP-g-MAH for potable water pipe applications. The materials were evaluated using a comprehensive suite of techniques, including microbiological assays, thermal analysis (TGA, DSC), mechanical testing, scanning electron microscopy (SEM), thermomechanical analysis (TMA), and contact angle measurements. The aim of this work is to identify an optimized HDPE/PP composition that delivers balanced mechanical, thermal, and antibacterial performance with direct relevance to sanitary water-pipe applications.

## Experimental

### Materials

High-density polyethylene (HDPE) and polypropylene (PP) granules were supplied by Saudi Basic Industries Corporation (SABIC). HDPE served as the base polymer, with PP added at varying weight percentages (5%, 10%, 15%, 20%). Polypropylene-grafted maleic anhydride (PP-g-MAH), with a particle size of 100 mesh and white in color, was sourced from a manufacturer in China and imported by Areej Al Furat Company (Baghdad) to act as a compatibilizer.

The compatibilizer content (1 wt% PP-g-MAH) was selected based on widely reported optimal ranges for HDPE/PP systems, where 0.5–2 wt% (0.5–2% by weight) is sufficient to enhance interfacial adhesion without causing phase saturation or excessive stiffness. Several studies have demonstrated that 1 wt% provides an effective balance between compatibility and processability in polyolefin blends, and therefore this ratio was adopted as the standard amount in the present work.

### Preparation of polymer blend samples

Polymer blends were prepared using a twin-screw extruder (manufactured in England) equipped with six heating zones, as illustrated in Fig. 1a. The temperature profile across all

**Fig. 1** Equipment used for sample preparation: **a** twin-screw extruder, and **b** thermal-hydraulic press



**Table 1** Composition (in weight percentage) of the prepared HDPE/PP blends, including the compatibilizer (PP-g-MAH)

| Sample         | A0  | A1 | A2 | A3 | A4 |
|----------------|-----|----|----|----|----|
| HDPE (wt%)     | 100 | 94 | 89 | 84 | 79 |
| PP (wt%)       | 0   | 5  | 10 | 15 | 20 |
| PP-g-MAH (wt%) | 0   | 1  | 1  | 1  | 1  |

zones was set to 250 °C. The polymer granules were fed into the extruder, which operated at a rotation speed of 2 rad/s. The molten blend was extruded through a rectangular die (150 mm × 100 mm × 5 mm) and subsequently transferred directly to a locally fabricated thermal-hydraulic press (Fig. 1b). The press platens were also maintained at 250 °C, and a pressure of 5 MPa was applied to the sample for 15 min. Finally, the pressed sample was quenched in a water bath to cool to ambient temperature. The compositions of the prepared blends are detailed in Table 1.

To ensure sample homogeneity, the molten polymer is spread under constant pressure and uniform temperature to guarantee even distribution and a homogeneous surface for all films. To ensure reproducibility, each formulation was manufactured using the same operating conditions, and no differences were recorded between the prepared batches.

A temperature of 250 °C and a pressure of 5 MPa were adopted based on preliminary experiments showing that these conditions are optimal for achieving good melt flow and ensuring effective mixing between HDPE and PP without thermal degradation. These values are also consistent with those reported in the literature on melting and processing of polyolefin-based polymers.

## Characterization

The prepared HDPE/PP composites were characterized using a suite of morphological, mechanical, thermal, and biological tests. The film thickness of all prepared samples ranged between 1.8 and 2.0 mm, measured using a digital micrometer to ensure uniform thickness across the specimens.

The examinations were performed using a scanning electron microscope with an accelerating voltage of 10–15 kV and magnifications ranging from 500 × to 5000 × after coating the samples with a thin gold layer. The contact angle was measured using a fixed droplet meter with a fixed volume of 5 µL. For bacterial examinations, absorbance readings were obtained at 570 and 590 nm after crystal violet staining using a photoabsorptometer. All measurements were performed under standard conditions to ensure the reproducibility of the results.

All mechanical and antibacterial measurements were performed in three independent replicates ( $n=3$ ), and the average values were reported. The standard deviation in all tests was less than 5%, which allowed presenting the results as mean values without error bars, while still preserving the validity of performance comparisons between samples.

## Morphological analysis

The surface morphology and microstructure of the blends were examined using scanning electron microscopy (SEM). This technique provides high-resolution images to evaluate polymer integration, homogeneity, and the presence of surface features such as cracks, pores, or phase separations [23].

## Mechanical testing

The resistance of the material to indentation, Hardness, was measured using a Durometer (Shore D scale) in accordance with ASTM D2240. Hardness values are influenced by interatomic and intermolecular bonding forces, with higher cohesion typically resulting in greater hardness [24]. The toughness, Impact strength, of the materials was evaluated using a Charpy impact test according to the ISO-179 standard. Samples were cut to specified dimensions (5.5 cm × 1 cm) for testing. A sample prepared for impact testing is shown in Fig. 2.

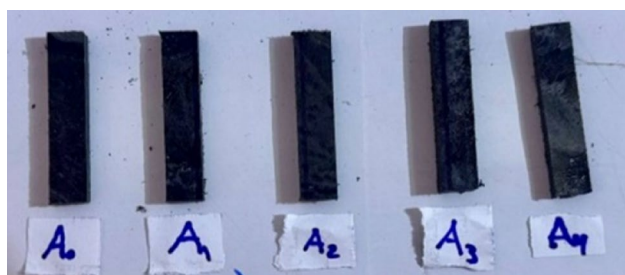


**Fig. 2** Photograph of a Charpy impact test specimen, prepared according to ISO 179 standards, mounted in the impact tester before fracture

### Bacteriological assay

Bacterial adhesion resistance was tested against two model strains: *Staphylococcus aureus* (Gram-positive) and *Escherichia coli* (Gram-negative). Samples were immersed in a bacterial suspension cultured in Tryptone Soya Broth (TSB) and incubated under standard conditions. The bacterial assay was performed using an inoculum of approximately  $10^6$  CFU/mL, with all samples incubated at 37 °C for 24 h, and a pure HDPE sample (A0) was used as the negative control [24, 25]. After incubation, the samples were rinsed to remove non-adhered cells and then stained with crystal violet for ten minutes. The stained biofilm was solubilized with 95% ethanol, and the solution's absorbance was measured via UV–Vis spectroscopy at 570 and 590 nm. A lower absorbance value corresponds to less bacterial adhesion on the polymer surface.

A pure HDPE sample (A0) was used as the control reference for all bacterial adhesion measurements. The absorbance values at 570 and 590 nm represent the quantified amount of crystal-violet-stained biofilm and are commonly used as a direct indicator of bacterial attachment on polymer surfaces. For this reason, the results were expressed as absorbance rather than converted to percentage reduction [26]. The relative decrease or increase in adhesion for each blend was evaluated by comparing its absorbance to the control (A0), which provides a valid and widely accepted method to assess antibacterial performance in polymeric materials [27].

### Surface wettability

The hydrophobicity of the blend surfaces was assessed by measuring the static water contact angle using a goniometer. A deionized water droplet was placed on the sample surface, and the angle formed between the solid surface and the water droplet's tangent was recorded. A higher contact angle indicates greater surface hydrophobicity [28].

### Thermal analysis

The thermal stability and decomposition profiles of the blends were analyzed using a thermogravimetric analysis (TGA) model Shimadzu Q600 analyzer. Samples (3–5 mg) were heated from 0 to 700 °C at a rate of 10 °C/min under a controlled atmosphere. Also, differential scanning calorimetry (DSC) was employed to investigate thermal transitions, including melting and crystallization behavior, by measuring heat flow differences between the sample and a reference as a function of temperature [29]. The thermomechanical analysis (TMA) was used to study dimensional changes (e.g., thermal expansion, shrinkage) in the materials under a controlled mechanical load as temperature was varied. This technique provides data on properties such as the coefficient of thermal expansion and softening points [30].

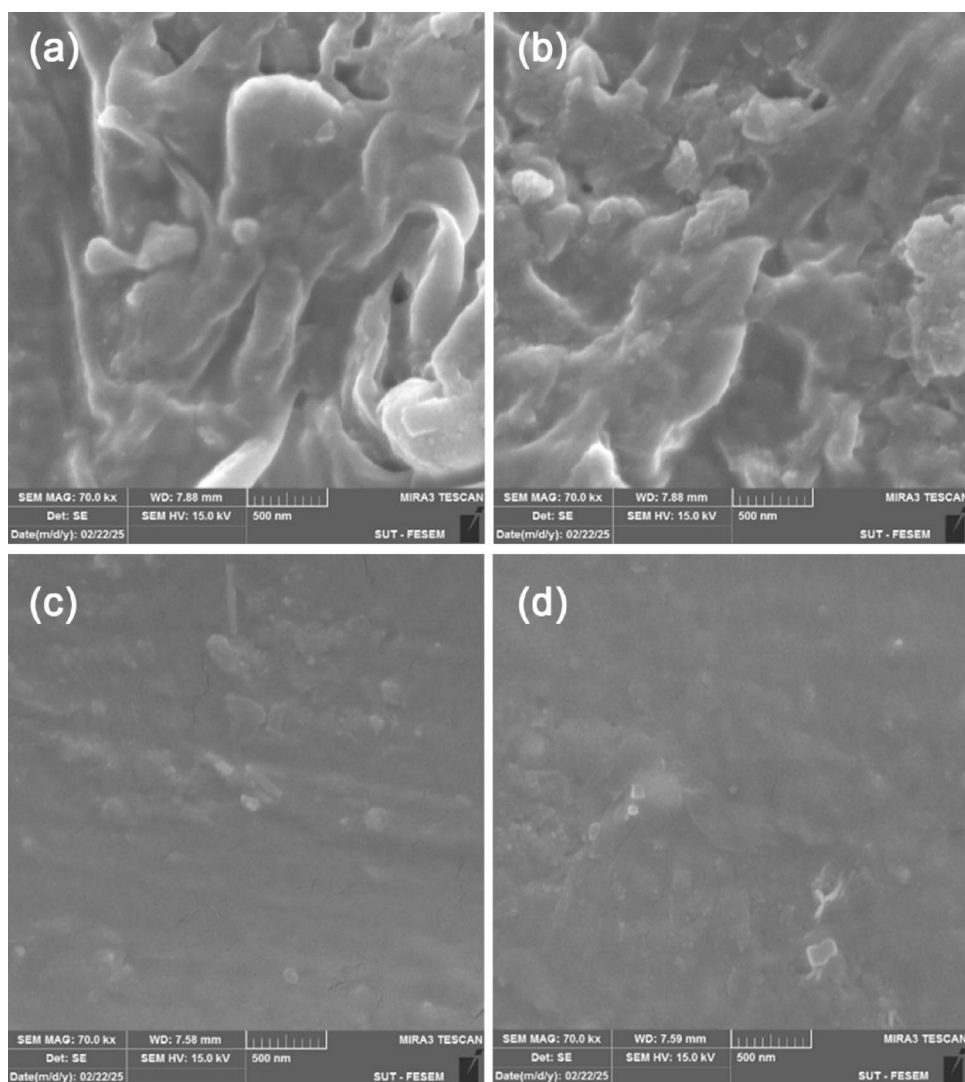
## Results and discussion

### Surface morphology

The morphology of polymer blends, as revealed by scanning electron microscopy (SEM), provides critical insight into the compatibility between constituent polymers and the efficacy of the compatibilizer. Figure 3 presents SEM micrographs of the HDPE/PP blends, each containing 1% PP-g-MAH but varying in their HDPE/PP ratios. The observed morphological changes directly correlate with blend composition and have profound implications for the material's final properties. The micrograph for sample A1 (94% HDPE / 5% PP / 1% PP-g-MAH), shown in Fig. 3a, demonstrates the initial effectiveness of the PP-g-MAH compatibilizer. The surface texture is markedly smoother with a significant reduction in voids and defects compared to a compatibilized blend. This improved morphology indicates that the compatibilizer is successfully facilitating interaction between the inherently immiscible HDPE and PP phases. The maleic anhydride groups in PP-g-MAH are theorized to interact with the polymer chains, reducing interfacial tension and promoting a more cohesive and uniform dispersion of the minor PP phase within the dominant HDPE matrix. This formation of a more continuous and integrated structure is a primary indicator of enhanced mechanical compatibility [31].

Upon increasing the PP content to 10% (sample A2, Fig. 3b), the SEM image reveals a slight increase in surface roughness, alongside the presence of minor cracks and pores. This suggests that while the 1% PP-g-MAH is still exerting a compatibilizing effect, evidenced by a morphology that is still superior to a pure blend, the increased proportion of the dispersed PP phase presents a greater challenge. The compatibilizer must now stabilize a larger interfacial

**Fig. 3** SEM micrographs of HDPE/PP blends compatibilized with 1% PP-g-MAH: **a** A1 (94% HDPE/5% PP), **b** A2 (89% HDPE/10% PP), **c** A3 (84% HDPE/15% PP), and **d** A4 (79% HDPE/20% PP)



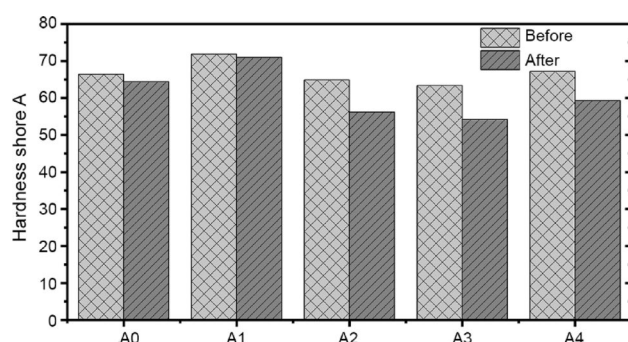
area, leading to slight phase separations and imperfections. The cracks are less pronounced than they would be without compatibilization, confirming that the PP-g-MAH is still mitigating, though not entirely preventing, phase separation at this ratio. A further increase to 15% PP (sample A3, Fig. 3c) reveals the growing insufficiency of the fixed 1% compatibilizer dosage. While the surface retains a degree of homogeneity, the emergence of small agglomerations is a clear sign of coalescence [32]. The dispersed PP particles begin to cluster together to minimize their interfacial energy, a phenomenon that occurs when the amount of compatibilizer is no longer adequate to fully cover and stabilize the entire interface between the two polymers. This indicates that compatibility is being compromised, and the blend is transitioning towards a more heterogeneous, two-phase system. This trend culminates in the morphology of sample A4 (20% PP), depicted in Fig. 3d. Despite the presence of the compatibilizer, the micrograph is dominated by large pores, voids, and clearly separated domains. The high PP content

has overwhelmed the capacity of the 1% PP-g-MAH to promote adhesion, resulting in severe phase separation. The components exhibit weak cohesion, with areas that appear entirely unbonded. This poor integration is a classical characteristic of immiscible polymer blends without adequate compatibilization and predicts inferior mechanical performance [33].

Based on morphological evidence alone, sample A1 presents the most optimal structure. The absence of clumps or significant phase separation, coupled with a smooth and homogeneous polymer distribution, suggests that the 1% PP-g-MAH is highly effective at this specific 94/5 HDPE/PP ratio. This level of compatibility is a prerequisite for good mechanical properties, as a cohesive structure allows for efficient stress transfer throughout the material. Furthermore, a smooth, non-porous surface is less likely to harbor bacteria, enhancing the material's suitability for sanitary applications like drinking water pipes. However, it is crucial to cross-reference this morphological analysis

**Table 2** Summary of SEM observations for HDPE/PP blend samples

| Sample | Surface homogeneity | Voids/Gaps       | Phase compatibility         | Overall morphology              |
|--------|---------------------|------------------|-----------------------------|---------------------------------|
| A0     | High                | None             | Single-phase                | Smooth and uniform surface      |
| A1     | Very high           | Very few         | Excellent (due to PP-g-MAH) | Best morphology                 |
| A2     | Good                | Small gaps       | Good                        | Balanced morphology             |
| A3     | Moderate            | Noticeable voids | Weak                        | Rough surface with porosity     |
| A4     | Poor                | Large voids      | Very weak                   | Highly heterogeneous morphology |

**Fig. 4** Hardness shore D of HDPE/PP blends before and after exposure to accelerated weathering

with mechanical, thermal, and biological property data to determine if the optimal morphology (A1) translates to the best overall performance, or if a blend like A2 offers a more favorable balance of properties for the intended application [34].

To simplify the results of the morphological analysis, a table (Table 2) was prepared summarizing the key observations derived from the SEM images of all samples, including the degree of surface homogeneity, the size of the gaps, and the level of compatibility between the polymer phases.

## Mechanical properties

To evaluate the durability and long-term performance of the HDPE/PP blends for potential outdoor or demanding applications, the samples were subjected to an accelerated weathering protocol. This involved exposing them to 140 h of cyclic conditions in a QUV tester, alternating between elevated temperature (60 °C), moisture condensation (50 °C),

and ultraviolet radiation (340 nm). Mechanical properties, namely hardness and impact resistance, were rigorously tested both before and after this accelerated aging process to isolate the effects of environmental degradation [35].

The Shore D hardness measurements, detailed in Fig. 4, provide critical insight into the material's resistance to surface deformation and its overall mechanical integrity. Prior to weathering, a clear correlation between blend composition and hardness was established. Sample A1 (94% HDPE / 5% PP) exhibited the highest hardness value (71.9), a direct consequence of its composition being dominated by the rigid, semi-crystalline structure of HDPE. The low percentage of PP was effectively dispersed and compatibilized within the HDPE matrix, creating a cohesive structure, as confirmed by SEM, which efficiently resists indentation. A gradual decrease in hardness was observed from samples A2 to A4. This trend is attributed to the increasing proportion of the less hard PP component and the corresponding deterioration of the crystalline HDPE structure. The SEM evidence for A3, which showed a fair distribution but increased amorphous content, aligns perfectly with this reduction in hardness [36].

Exposure to UV radiation, heat, and humidity induced photo-oxidative degradation in all samples, manifesting as a measurable decrease in hardness due to polymer chain scission [37]. The extent of this degradation, however, was highly dependent on the blend composition. Sample A0 (100% HDPE) showed only a minor loss in hardness, consistent with its known relative UV resistance. Most significantly, Sample A1 demonstrated the best retention of hardness post-weathering (from 71.9 to 71.0). This superior performance is a direct result of its optimal morphology—the compatibilized, homogeneous, and void-free structure minimizes surface area for UV attack and provides inherent stability against environmental stress [38]. In contrast, samples with higher PP content (A2–A4) suffered more substantial losses. This is because PP is inherently more susceptible to UV degradation than HDPE. For instance, sample A3, with 15% PP, showed the highest loss in hardness. Its morphology, which began to show agglomerations and reduced compatibility (as seen in SEM), created pathways for deeper UV penetration and structural weakening. The behavior of sample A4, while still showing significant degradation, was slightly less severe than A3, potentially due to a different phase distribution or its higher initial hardness; however, its SEM-confirmed voids and pores still led to rapid degradation. The TMA results, which indicated higher thermal expansion and thus weaker chain bonding in these samples, further corroborate the accelerated weathering-induced decline in mechanical strength [39].

The Charpy impact test results, summarized in Fig. 5, evaluated the material's toughness, or its ability to absorb

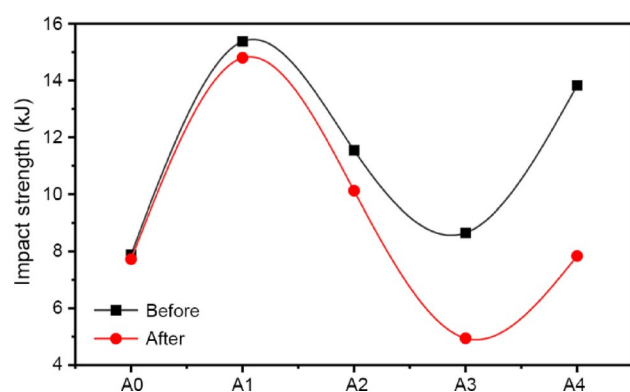


**Fig. 5** Impact strength of HDPE/PP blends before and after exposure to accelerated weathering

energy and plastically deform without fracturing under sudden load. Sample A0 exhibited low but stable impact resistance, a characteristic of the homogeneous but less tough pure HDPE. The incorporation of 5% PP in sample A1 resulted in excellent impact resistance that was largely retained after weathering. This remarkable toughness is a classic benefit of a well-compatible blend, where the dispersed rubbery PP particles within the rigid HDPE matrix act to initiate and terminate micro-cracks, thereby absorbing significant energy. The homogeneous, well-bonded morphology observed in SEM is essential for this mechanism to function effectively. Sample A2 maintained a good, albeit reduced, balance of toughness and strength after aging. The deterioration in samples A3 and A4, however, was severe. Although their impact resistance before weathering was reasonable, it deteriorated dramatically after UV exposure [40]. This is a direct consequence of their poor morphology, as identified by SEM. The voids, pores, and phase-separated regions act as critical stress concentration points, providing ideal sites for cracks to initiate and propagate catastrophically, especially after the polymer chains have been embrittled by UV degradation [41].

The mechanical property analysis unequivocally demonstrates that the blend's performance is a direct function of its morphology, which is controlled by the PP content and the efficacy of the compatibilizer. Sample A1, with its optimal 94/5 HDPE/PP ratio, delivers the most superior and durable mechanical profile, combining high initial hardness, exceptional impact toughness, and most importantly, outstanding retention of these properties after accelerated weathering. This makes it the most mechanically reliable formulation for applications requiring long-term environmental exposure.

### Bacterial adhesion and surface wettability analysis

The propensity for bacterial colonization on the polymer blends was quantitatively assessed using a crystal violet

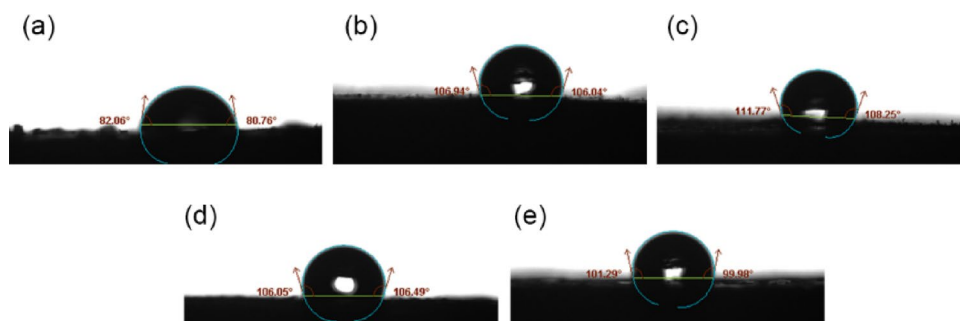
**Table 3** Antibacterial activity of HDPE/PP blends (absorbance values; lower value indicates less bacterial adhesion)

| Sample         | <i>S. Aureus</i><br>(570 nm) | <i>E. Coli</i><br>(570 nm) | <i>S. Aureus</i><br>(590 nm) | <i>E. Coli</i><br>(590 nm) |
|----------------|------------------------------|----------------------------|------------------------------|----------------------------|
| A <sub>0</sub> | 1.608                        | 1.694                      | 1.763                        | 1.734                      |
| A <sub>1</sub> | 1.130                        | 1.980                      | 1.258                        | 2.118                      |
| A <sub>2</sub> | 1.725                        | 1.192                      | 1.868                        | 1.314                      |
| A <sub>3</sub> | 1.730                        | 1.633                      | 1.882                        | 1.211                      |
| A <sub>4</sub> | 1.932                        | 1.477                      | 2.070                        | 1.736                      |

staining assay, with results for *Staphylococcus aureus* (Gram-positive) and *Escherichia coli* (Gram-negative) detailed in Table 3. This method, coupled with UV-Vis spectrophotometry, provided absorbance values that served as an indirect measure of adhered bacterial biomass, where higher values indicate greater colonization. The results revealed a complex interplay between polymer composition, surface morphology (as previously seen in SEM), and bacterial adhesion tendencies. Pure HDPE (sample A0) exhibited relatively high adhesion for both bacterial strains. This is characteristic of an unmodified hydrophobic polymer surface, which, while lacking specific affinity, provides a suitable substrate for initial bacterial attachment [42].

A critical finding emerged from the analysis of the compatibilized blends. Sample A1 demonstrated the lowest adhesion for *S. aureus* but, conversely, the highest adhesion for *E. coli*. This apparent contradiction can be explained by the distinct adhesion mechanisms of the two bacteria. The spherical cocci of *S. aureus* are potentially hindered by the moderately rough and heterogeneous morphology of A1 observed in SEM. In contrast, the rod-shaped *E. coli* cells may exploit these same micro-scale crevices and the hydrophobic nature of the surface for enhanced anchoring, leading to increased colonization. Conversely, sample A2 presented a highly favorable profile for sanitary applications [43]. It recorded the lowest adhesion for *E. coli*, a critical indicator organism for fecal contamination in water systems. Although its adhesion for *S. aureus* was higher, its performance against *E. coli* is paramount for water safety. This resistance is attributed to its smooth, highly compatible, and homogeneous surface morphology (SEM), which minimizes topographical features that rod-shaped bacterium like *E. coli* uses for mechanical anchoring. Samples A3 and A4, with higher PP content, showed increased adhesion for both strains, particularly *S. aureus*. This is a direct consequence of their poor morphological integrity, as evidenced by SEM, where voids, pores, and phase separation create ideal niches for microbial entrapment and biofilm formation, overriding any beneficial effects of compatibilization. To further elucidate these adhesion mechanisms, surface wettability was analyzed through contact angle measurements (Fig. 6). This revealed a significant shift from the relatively hydrophilic nature of pure HDPE (A0, ~81°) to

**Fig. 6** Water contact angle images for HDPE/PP blends **a** A0, **b** A1, **c** A2, **d** A3, and **e** A4



the pronounced hydrophobicity of all compatibilized blends (A1–A4, contact angles  $> 90^\circ$ ). However, hydrophobicity alone was not a definitive predictor of anti-fouling performance [44].

The combination of wettability and topography provides the clearest explanation. Sample A1 ( $106^\circ$ ) shows high hydrophobicity combined with a rough morphology, creating an ideal surface for the hydrophobic *E. coli* to adhere. Sample A2 ( $111.8^\circ$ ) possesses the highest hydrophobicity and the smoothest morphology, and this ultra-smooth surface minimizes attachment points, effectively repelling the rod-shaped *E. coli* despite the favorable hydrophobic interaction. Samples A3 and A4 ( $\sim 106^\circ$  and  $\sim 100^\circ$ ) have hydrophobic surfaces compromised by porous and heterogeneous topography (SEM), and these physical defects provide abundant harborage sites that facilitate adhesion for both bacterial types, demonstrating that poor morphology can exacerbate biofilm formation even on a hydrophobic surface. The bacterial adhesion assay, interpreted in the context of SEM and contact angle data, identifies sample A2 as the most promising material for potable water pipe applications. While sample A1 excels against *S. aureus*, its high susceptibility to *E. coli* colonization renders it a less suitable choice for preventing waterborne contamination. Sample A2's superior performance is derived from its optimal surface characteristics: a smooth, homogeneous morphology that minimizes bacterial anchoring points, coupled with high hydrophobicity [45]. This combination effectively limits the adhesion of the critical pathogen *E. coli*, thereby directly addressing the primary bacteriological risk in drinking water distribution systems.

Although morphological analysis showed that sample A1 possessed superior surface homogeneity and fewer defects compared to the other samples, this structural advantage did not translate into improved biological performance. Bacterial adhesion and contact angle measurements revealed that sample A2 exhibited significantly lower *E. coli* adhesion and a marked increase in hydrophobicity, as illustrated in Table 2 and Fig. 6. These characteristics are particularly important in sanitary water pipe applications, where resistance to bacterial growth is a crucial factor that outweighs minor differences in surface structure. Therefore, despite

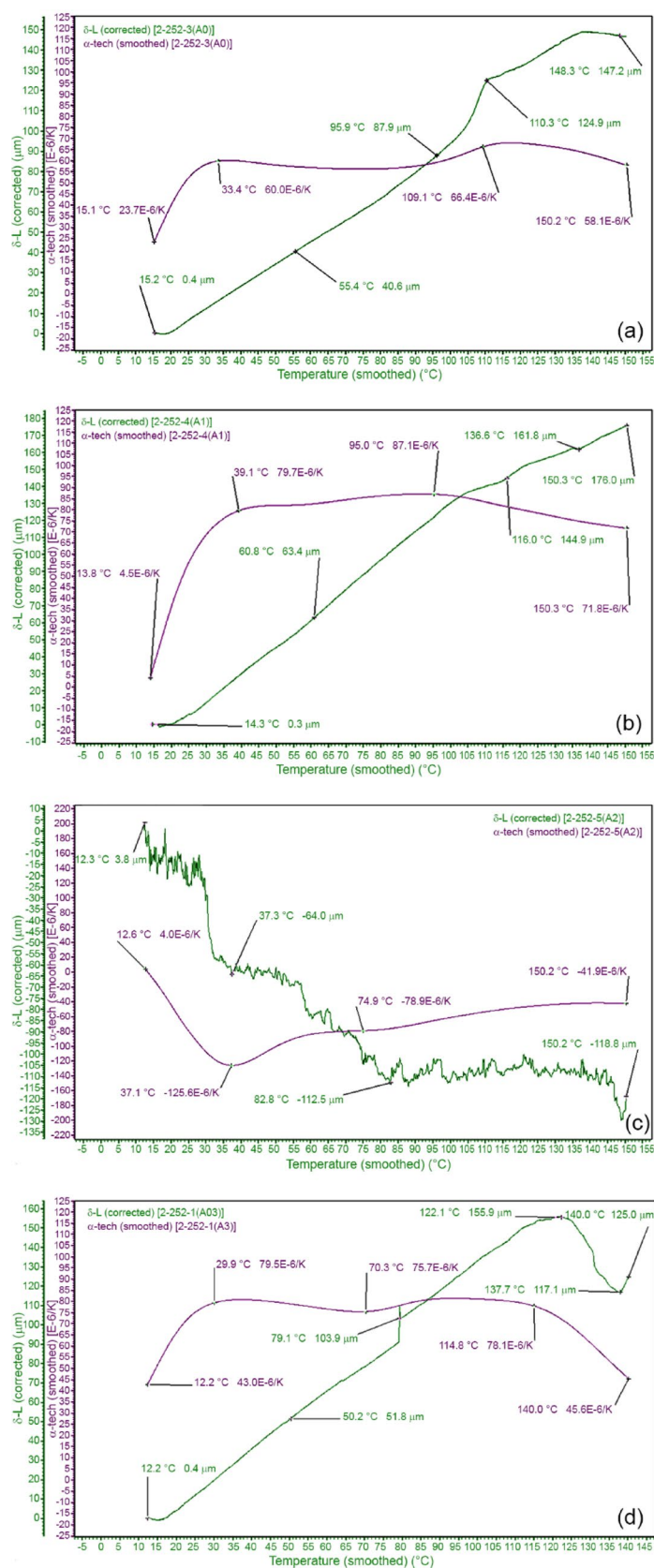
A1's morphological superiority, a comprehensive evaluation of its mechanical, thermal, and biological properties demonstrates that sample A2 offers more balanced performance and is better suited for practical applications.

### Thermal and thermomechanical characterization

The thermal stability and dimensional response of the polymer blends to temperature fluctuations were critically evaluated using thermomechanical analysis (TMA), thermogravimetric analysis (TGA), and differential scanning calorimetry (DSC). These analyses provide essential insights into the material's performance under thermal stress, a crucial factor for applications like water pipes that may experience hot water exposure and environmental temperature changes.

The TMA results, detailed in Fig. 7, revealed significant differences in dimensional stability and coefficient of thermal expansion (CTE) across the blends. Pure HDPE (sample A0) exhibited a typical gradual thermal expansion profile, with its CTE increasing to a maximum near its melting point before mechanical weakening commenced. In contrast, sample A1 demonstrated markedly superior thermal dimensional stability. Its reduced longitudinal expansion and lower CTE are a direct benefit of the compatibilized structure; the PP-g-MAH enhances interfacial adhesion, creating a more rigid network that restrains polymer chain movement and expansion under heat. Sample A2 exhibited a highly distinctive thermomechanical signature: an anomalous contraction event at approximately  $37^\circ\text{C}$ . This slight contraction near  $37^\circ\text{C}$  can be explained by localized rearrangement and relaxation of polymer chains within semi-crystalline regions before normal thermal expansion resumes [46]. This suggests a significant internal rearrangement or stress relaxation within the specially compatibilized blend, indicating a highly interactive morphology. Conversely, samples A3 and A4 displayed poor thermal stability. Their high and erratic CTE values, culminating in severe expansion (A4 reached  $215\ \mu\text{m}$ ) and eventual structural collapse at high temperatures, are direct consequences of their phase-separated morphology. The voids and weak interfaces observed via SEM provide pathways for uncontrolled expansion, rendering

**Fig. 7** TMA analysis of HDPE/PP blends **a** A0, **b** A1, **c** A2, **d** A3, and **e** A4



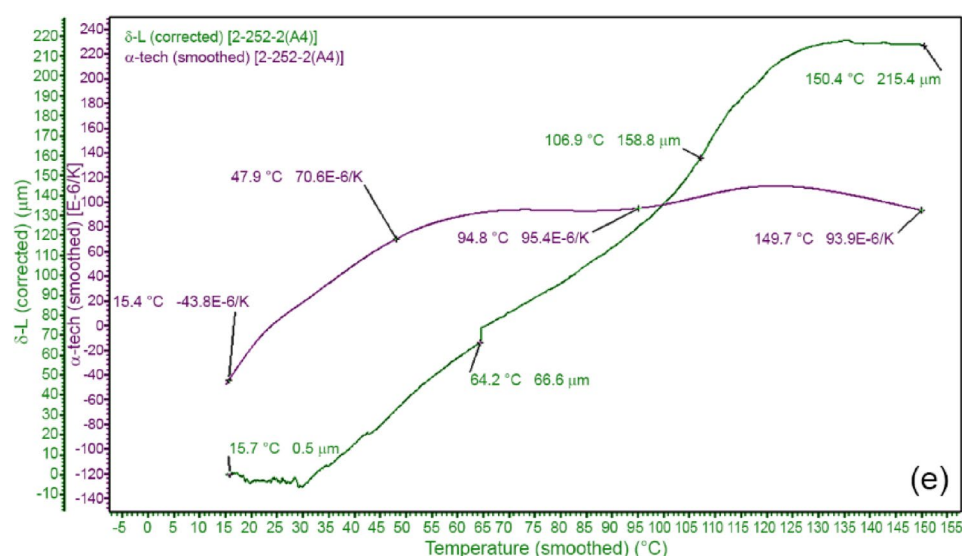


Fig. 7 (continued)

**Table 4** Comparative analysis of thermal properties of HDPE/PP blends with 1% PP-g-MAH. begin of decomposition ( $D_b$ ), end of decomposition ( $D_e$ ), percentage weight loss ( $m_{loss}$ ), melting point ( $T_m$ ) and heat of fusion ( $\Delta H$ )

| Sample | $D_b$ (°C) | $D_e$ (°C) | $m_{loss}$ (%) | $T_m$ (°C) | $\Delta H$ (J/g) |
|--------|------------|------------|----------------|------------|------------------|
| A0     | 415.11     | 451.18     | 87.33          | 132.4      | 188.5            |
| A1     | 442.17     | 464.54     | 68.37          | 131.8      | 165.3            |
| A4     | 438.63     | 454.63     | 83.46          | 133.1      | 121.7            |

these blends dimensionally unstable and unsuitable for applications requiring thermal reliability.

The DSC curves of the different samples showed clear melting peaks for the predominant HDPE phase within the typical temperature range for polyethylene (130–135 °C), as evident in Table 4 and Fig. 8b. These peaks reflect stable crystalline behavior and a uniform thermal distribution in the blends with higher structural homogeneity, particularly in samples A1 and A2. The incorporation of PP-g-MAH improved interfacial bonding between the polymer phases, reduced phase separation, and produced more consistent melting peaks with fusion enthalpy ( $\Delta H$ ) values that remain within the acceptable range for compatibilized HDPE/PP systems.

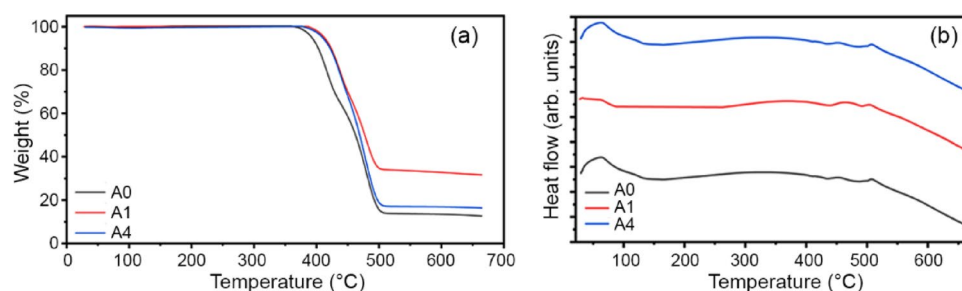
In contrast, samples with higher PP content (A3 and A4) exhibited lower fusion enthalpy and weaker melting

responses, indicating reduced crystallinity and diminished thermal coherence. This behavior is associated with increased porosity and poorer interfacial compatibility, as supported by SEM observations and mechanical results. These variations in melting behavior and  $\Delta H$  values confirm the strong effect of blend composition on crystalline stability and the overall thermal performance of the studied HDPE/PP samples.

The DSC thermograms (Fig. 8b) detailed the melting and crystallization behavior. While distinct melting peaks for both HDPE (~63–67 °C) and PP were evident, the compatibilized blends showed crucial differences in their thermal signatures. Sample A1 exhibited significant new thermal events, including a substantial fusion peak at

~262 °C and a crystallization peak at ~367 °C. These events are indicative of new crystalline structures forming at the interface between HDPE and PP, facilitated by the compatibilizer. This improved interaction explains the enhanced mechanical and thermal properties observed in A1. In contrast, the DSC curve for sample A4 showed a much lower heat of fusion for its high-temperature events, indicating poor thermal homogeneity and weak interfacial bonding, which aligns perfectly with its porous SEM morphology and inferior performance.

**Fig. 8** a TGA curves, and b DSC curves of HDPE/PP blends



The thermal analysis suite conclusively demonstrates that the efficacy of the 1% PP-g-MAH compatibilizer is dependent on the HDPE/PP ratio. Sample A1 emerges with the most robust thermal profile. It possesses the highest decomposition onset temperature, indicating superior thermal stability; shows evidence of a new, well-compatibilized crystalline structure; and exhibits the best dimensional stability with the lowest CTE. This combination of properties ensures that A1 would maintain its structural integrity and dimensions under thermal cycling, a critical requirement for hot water piping systems. The deterioration in performance seen in samples A2 through A4 underscores a critical finding: beyond an optimal ratio, increasing the PP content overwhelms the compatibilizer's capacity, leading to phase separation that severely undermines both mechanical and thermal properties [47]. Therefore, based on thermal performance, A1 is identified as the most suitable formulation.

## Conclusion

This study successfully developed and characterized a series of HDPE/PP blends compatibilized with 1% PP-g-MAH. A comprehensive evaluation through morphological, mechanical, thermal, and biological assays demonstrated that the blend composition critically determines the final properties and suitability for sanitary water pipe applications. The key finding of this research is the identification of an optimal formulation that balances all critical performance metrics. While sample A1.

(94% HDPE/5% PP/1% PP-g-MAH) exhibited excellent mechanical properties, superior thermal stability, and the most homogeneous morphology, sample A2 (89% HDPE/10% PP/1% PP-g-MAH) emerged as the most well-rounded and suitable candidate. A2 demonstrated an ideal combination of good mechanical strength, high thermal stability, the lowest coefficient of thermal expansion, and, most importantly, exceptional resistance to bacterial adhesion, particularly against *E. coli*. This superior bacteriological performance, a result of its optimally hydrophobic and smooth surface, is the paramount factor for drinking water applications, outweighing other considerations. In contrast, samples A3 and A4, with higher PP content (15% and 20%), displayed significant shortcomings. Their poor morphological integrity, evidenced by phase separation, voids, and agglomerations, led to inferior mechanical strength, reduced thermal stability, and higher bacterial colonization, rendering them unsuitable for the intended application. Therefore, it is concluded that the A2 blend (89% HDPE/10% PP/1% PP-g-MAH) represents the optimal formulation. It successfully leverages the compatibilizer to create a material that meets the stringent requirements for mechanical durability,

thermal resistance, and sanitary safety essential for manufacturing potable water distribution pipes. However, this study has certain limitations. The compatibilizer content was fixed at 1 wt% without exploring a broader optimization range, and long-term aging or environmental stability tests were not included. In addition, the current preparation method was evaluated at laboratory scale, and further work is needed to assess processing challenges and performance consistency under industrial manufacturing conditions.

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**Data availability** The data that support the findings of this study are available from the corresponding author upon reasonable request.

## Declarations

**Conflict of interest** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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