CHAPTER 4

Development of Waterborne Polyurethane Polymers using Castor oil

4.1. Introduction

Polyurethane (PU) is a widely used polymer in domestic, industrial, and technical fields because of its tailor-made properties and easy applicability.[1–4] Generally, the preparation of conventional solvent-based PU involves, isocyanates, and polyols, mainly derived from petroleum sources, which results in the addition of numerous harmful air pollutants and volatile organic compounds (VOCs) to the environment.[5,6] As the extensive applications increase the demand for PU polymers, and at the same time, environmental pollution concerns increase, there is a need for an alternative to solvent-based PUs.

Nowadays, waterborne polyurethane (WPUs) have emerged as the best alternative to conventional solvent-based PU and are widely researched.[7,8] Polyaddition reactions involving diisocyanates as hard parts and polyols as soft parts prepare the WPU. [9] The soft parts of WPU contribute to its flexible characteristics, while the hard parts affect the mechanical and thermal stability of the PU materials. With the different compositions of soft and hard parts, WPUs demonstrate a distinct microphase separation. To control how much this microphase separation happens in WPUs, one can get excellent mechanical strength, good flexibility, and good resistance to solvents.[10] Hence, with this versatility, WPUs have been shown to have diverse applications, including as glass fiber lubricants,[11–13] elastomers,[14] adhesives,[15,16] textile finishes,[17] and the base coating for leather products, plastics, furniture, flooring, automotive, vinyl upholstery, and footwear.[18,19] The main parts used to synthesize WPU come from petroleum sources: polyols, diisocynates, and hydrophilic chain extenders.[20] Hence, with the increased demand for WPUs and the concerns about environmental sustainability, the production of WPUs using renewable bioresources instead of petroleum compounds has become a more important and urgent requirement.

In this context, the replacement of petroleum-based polyols with vegetable oil (VO) and the development of WPU polymers with similar or improved properties are the major demands of current research.[21] Due to their excellent properties, such as low toxicity, inherent biodegradability, high purity, etc., the vegetable oils involved in the production of WPUs are gaining much importance.[22] Not only that, a main focus is employed on utilizing the nonedible castor oil (CO) as the polyols,[23] for WPU preparation has been largely substituting petroleum-based polyols. CO is a good NEVO because it is biodegradable, low-cost, available, and its structure contains hydroxyl groups and unsaturation. Also, CO containing active hydroxyl groups can react with isocyanate directly without any further modification.[24] Using CO, both cationic and anionic WPUs have been successfully developed by Liang et al.[25] and show better storage stability at RT with adjustable mechanical properties. Also, the cationic WPU had better antibacterial activity.

WPUs also find extensive application as finishing agents in textiles to enhance fabric durability, improve quality, and achieve a more refined appearance. Additionally, they are employed to create coatings that promote breathability and are free from formaldehyde.[26] The exceptional qualities of WPUs, like hydrophilic, antistatic, and anti-dust properties, make them especially well-suited for synthetic fibers.[27] Throughout manufacturing, working, transportation, and storage, the textile fabrics can be susceptible to microbial organisms. These microorganisms possess the ability to infect textiles, leading to fiber deterioration, unpleasant smells, and a slick and slimy texture.[28] In this aspect, to protect textile fabrics from expected microbial infections, antibacterial coating of fabrics was counted the best solution.[29] Many chemical finishing agents like chitosan, triclosan, metal nanoparticle materials and quaternary ammonium salts have been used for antimicrobial coating of textile fabrics.[30,31] Moreover, polyphenolic compounds (vanillin, curcumin, and tertiary butyl hydroquinone) are also used to enhance antimicrobial properties.[30,32,33]

Curcumin is sourced from the plant *curcuma longa* and inherent variety of pharmacological properties.[34] Biocompound curcumin manifests potent antimicrobial, antioxidant, antiinfammatory, anticoagulant, and antitumor activities.[35,36] Curcumin has also been used as antimicrobial agent for wounds.[37] Traditionally, it is used for dying or coloring the fabrics.[38] In this study, curcumin was used as a bioresource to develop CO-based WPU as a chain extender because of its ability to apply strong antibacterial properties to the fabrics. The incorporation of naturally occurring bioactive curcumin into the polymeric chain of CO-based WPUs represents a more effective approach in the development of WPU. This addition significantly contributes to enhancing the antibacterial characteristics of polyester/cotton (PE/C) blend fabrics when coated.

In the present work, the new WPUCs (Waterborne polyurethane alongwith bioactive curcumin) polymers are synthesized using CO as a polyols and curcumin as the chain extenders. The impact of different mole ratio of curcumin on the synthesis of WPUCs has been investigated. The synthesized WPUCs are characterized through the ATR-FTIR, DLS, and Zeta potential techniques. The synthesized WPUCs is coated on the PE/C blend fabric by dip coating technique. Analyses of the color fastness, air permeability, abrasion resistance, bending modulus, and tensile strengths of WPUC-coated PE/C blend fabric are investigated to determine its durability, permeability and mechanical properties. The antibacterial studies of the WPUC-coated PE/C blend fabric have been performed against gram-positive and gram-negative bacteria for its better antibacterial textile applications.

4.2. Experimental

4.2.1. Materials

Dimethylol propionic acid (DMPA) and curcumin were received from sigma Aldrich India. isophorone diisocyanate (IPDI) and triethylamine (TEA) were procured from Merck India. Dibutyltin dilaurate (DBTDL) and methyl ethyl ketone (MEK) and were obtained from TCI Chemicals India. The polyester/cotton (PE/C) blend fabric was purchased locally. The specifications of the studied PE/C blend fabrics are shown in **Table 4.1**. The PE/C blend fabric was cleaned in the bath using the detergent at 100°C for 30 minutes. After the impurities like dust and oil stains were removed, the fabric was rinsed with both warm and cold water and then left to air dry at RT before use. The pH levels of the fabric remained steady between 6.5 and 7.5 during the various treatment stages.

Table 4.1. Specifications of PE/C blend fabric sample

Quality	Plain weave polyester/cotton
Appearance	White
Count (Warp-wise /Weft-wise)	33/31
Blend ratio polyester/ cotton	67/33
GSM (g/m^2)	123.2
EPI[a]	108
PPI[b]	88

[a]Ends per inch, [b]Picks per inch.

4.2.2. Methods

4.2.2.1. Synthesis of WPUCs dispersions

The overall reaction process to synthesize WPUCs using the bioresources CO and curcumin is shown in **Figure 4.1** and has been previously reported with synthetic polyol.[39] The synthesis of WPUC having two-step reactions. In the first step, dry CO and IPDI were taken in a RBF equipped with a mechanical stirrer, thermometer, and N_2 inlet for 30 min at 80°–90°C. A drop of the DBTDL and the DMPA emulsifier was added to the reaction content under the stirring. Here, the mole ratio of the -NCO groups (IPDI), -OH group (CO), and the emulsifier-OH groups (DMPA) was 2.5:1.0:0.9. The reaction mixture was further kept to react for 2 hrs at 80°C to synthesize the PU-prepolymer. Then, TEA was added as a neutralizing agent, and reaction was continued for the next 45 min at 55°C to get neutralized

PU-prepolymer. For lowering the viscosity of the polymer solution, a very small amount of MEK was added to the reaction content. The extension of polymer chain of the neutralized PU-prepolymer was done using the incorporation of curcumin (solubilized in the required MEK solvent) for 30 min, followed by the dropwise addition of the decided water under continuous stirring. The dispersion step was again proceeding for the next 2 hrs at RT.

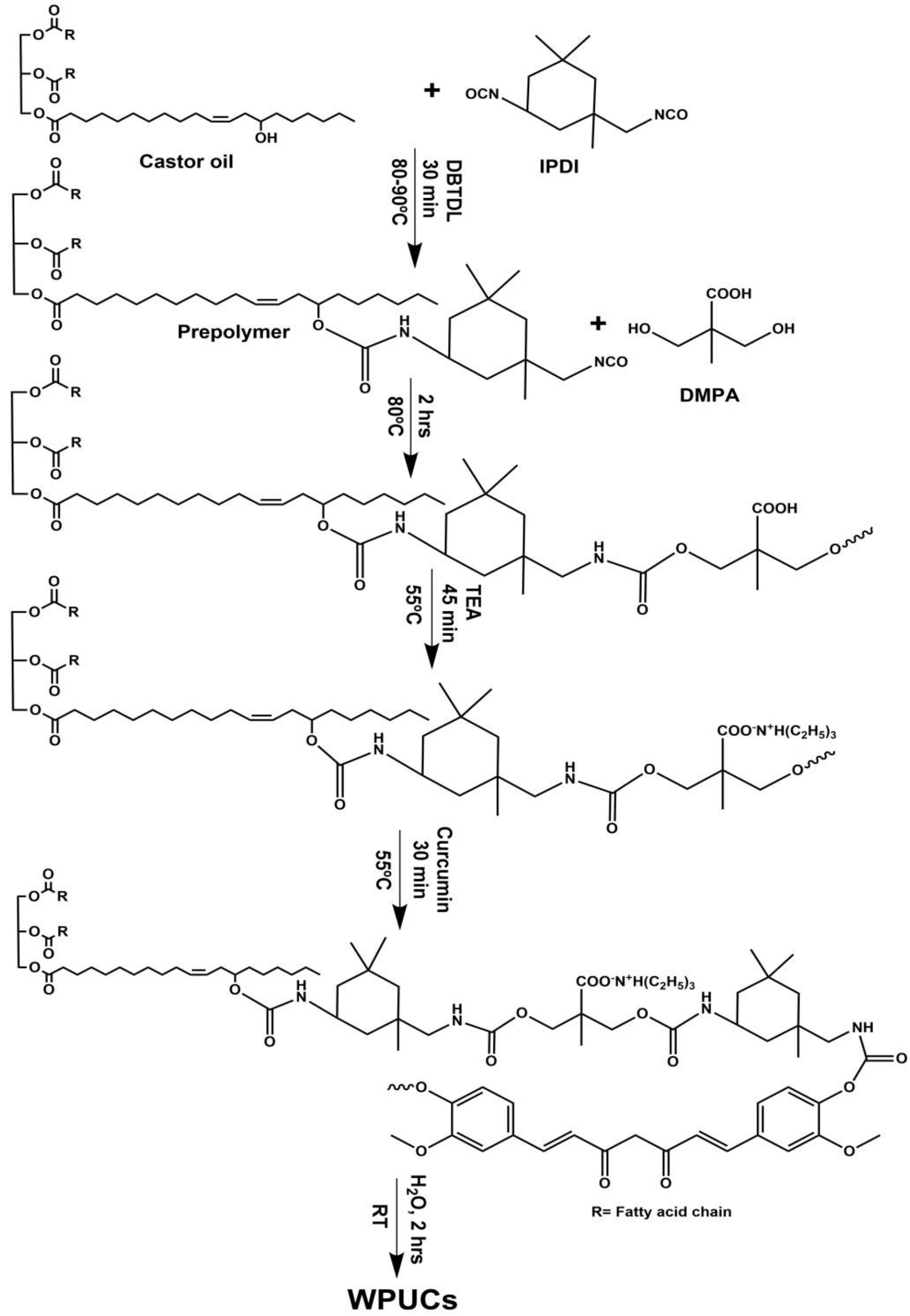

Figure 4.1. Synthetic scheme of WPUCs synthesis

After that, the MEK was removed from WPU dispersion using a rota-evaporator to yield WPU dispersion with a 30% solid content. The use of MEK solvent is essential here, but it's not good for the environment. The MEK is distilled out completely, but its residual presence may not be a better practice in the synthesis. The replacement of this important solvent is very necessary in the PU synthesis chemistry. From the above-mentioned process, the WPU without curcumin and the other three polymers with different mole ratios of curcumin were synthesized. The composition of all the synthesized WPUCs is shown in **Table 4.2.** The physical appearance of synthesized WPUCs is displayed in **Figure 4.2**.

Table 4.2. Composition of the WPUCs

Sample	CO (moles)	IPDI (moles)	DMPA (moles)	TEA (moles)	Curcumin (millimole)
WPUC0	1.0	2.5	0.9	0.9	0.0
WPUC0.1	1.0	2.5	0.9	0.9	0.1
WPUC0.5	1.0	2.5	0.9	0.9	0.5
WPUC1	1.0	2.5	0.9	0.9	1.0

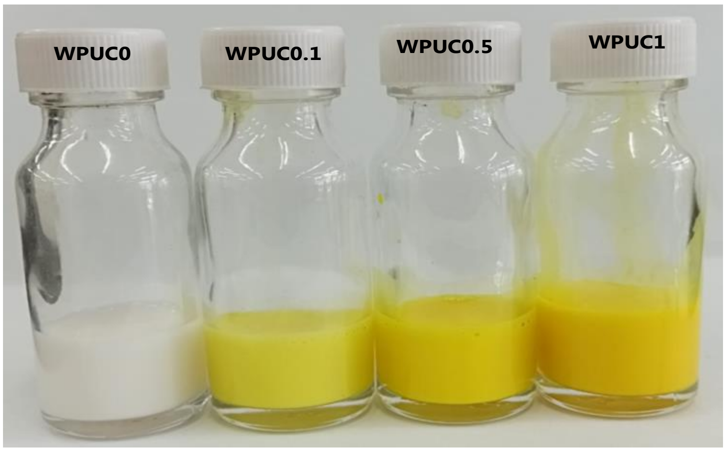

Figure 4.2. The appearance of WPUCs with different molar ratio of curcumin

4.2.2.2. Coating of WPUCs on PE/C blend fabric

The PE/C blend fabric was coated with synthesized WPUCs (shown in the **Figure 4.3**) using the dip coating technique. After coating, the coated fabric was dried at 115°C for 5 min. To achieve the desired characteristics, the fabric underwent three coating cycles, resulting (shown in **Table 4.3**) in an add-on ranging from 27.98% to 38.64 % of polymer coating with thickness of ~0.1 mm.

Table 4.3. Measured characteristics of the WPUC-coated PE/C blend fabrics

Sample	GSM	Thickness (mm)	Coating (%)	After coating fabric appearance
Uncoated	123.2	0.22	00.00	-
WPUC0	170.8	0.31	38.64	White
WPUC0.1	158.8	0.30	28.90	Light yellow
WPUC0.5	154.4	0.29	25.32	Yellow
WPUC1	157.6	0.31	27.98	Dark yellow

Figure 4.3. WPUCs-coated PE/C blend fabrics

4.2.3. Characterization

4.2.3.1. Physical characteristic

Physical characterizations of all the synthesized WPUC dispersions have been done to examine their dispersion stability and appearance. All samples were centrifuged (3000 r/min, 30 min) at 25 °C on a REMI R4C centrifuge to evaluate their stability.[40] **"**The solid contents of WPUCs have been determined by following the ISO124-1997 standard method. Placing a fixed amount of WPUC dispersion in an aluminum cup and drying it in a vacuum oven at 80°C until the weight of the solid contents was constant. The solid contents were then calculated using the following equation:

$$\text{Solid contents}(\%) = \frac{\text{A}-\text{B}}{\text{D}} \times 100$$

Where, B = mass of empty aluminium cup, D = mass of the cup and WPUC before drying, and A= mass of cup and WPUC after complete drying.**"**

4.2.3.2. Dispersion size distribution

Using a Zetasizer (Malvern, Na model UK), a DLS method was used to measure the particle size and distribution of the WPUC dispersion. The WPUC dispersion samples were diluted to a 5 mg/mL with distilled water and further sonicated for the analysis.

4.2.3.3. Structural characterization

ATR-FTIR spectroscopic measurements were used to characterize the molecular structure of curcumin and WPUCs. ATR-FTIR spectra were recorded in the range 4000-400 cm^{-1} on a Bruker Tensor 11 spectrometer. The spectrum of the air was taken as a background before each sample analysis. The ATR-FTIR were used to confirm the formation of WPUCs.

4.2.3.4. Fastness Properties of WPUC-coated PE/C blend fabrics

The standard methods were employed to assess the washing, light, and rubbing fastness characteristics of the WPUC-coated PE/C blend fabric samples. To determine wash fastness, the relevant ISO-1006-C03 (ISO 3) technique was employed. A fabric piece of 5 x 2 cm^2, to be tested, was positioned between two adjacent uncoated fabrics of identical dimensions. The fabric sample was stitched along all four sides to create a combined sample. This composite sample was immersed in a bath containing a soap solution of 5 gm/L and a soda ash solution of 2 gm/L, maintaining a fabric-to-liquor ratio of 1:50. The bath was sealed and placed in a water bath, where it underwent a 30 min treatment at a temperature of 60°±20°C. After the treatment cycle, the samples were extracted, rinsed with distilled water, gently squeezed, and air-dried. The alteration in shade was evaluated and ranked on a scale of 1 to 5 using the greyscale method, with 1 indicating poor and 5 signifying excellent resistance to washing.

The light fastness of the coated fabric samples was determined using the BSI006:1987 method, which involved subjecting the samples to 16 hrs of sunlight exposure. The assessment of light fastness was conducted by contrasting the exposed section with the unexposed portion of the material. Ratings were assigned on a scale from 1 to 8, with 1 indicating inadequate light fastness and 8 representing exceptional resistance to light.

Assessing the ability to resist rubbing (both when wet and dry) using a crock meter (BS1006; NOX12; 1978) was performed. The rubbing test apparatus employed a finger with a diameter of 1-6 cm, moving back and forth in a straight line across a 10 cm track on the sample with a 6 N forward force. The crock meter served as a suitable device for this purpose. The samples were tested against a rubbing cloth made of coated fabric measuring 5x5 cm^2. Two sets of fabric samples were prepared for dry rubbing and wet rubbing. In both scenarios, the rubbing motion was repeated 10 times over 10 seconds along the specified track. For the wet rubbing test, the cloth was wetted and wrung until it retained its water weight. The extent of staining on the rubbing cloth was evaluated using a greyscale and rated on a scale of 1 to 5, where 1 indicates poor resistance to rubbing and 5 indicates excellent resistance.

4.2.3.5. Air permeability of WPUC-coated PE/C blend fabrics

The air permeability measurements were made using the Air Permeability Tester in accordance with ASTM D1737-96 at a set pressure of 200 Pa. Ten repetitions for each WPUC-coated PE/C blend fabric sample were made.

4.2.3.6. Mechanical properties of WPUC-coated PE/C blend fabrics

The mechanical performance testing such as abrasion, bending modulus, and tensile strength of plain weaved PE/C blend fabric samples and after being coated with different WPUCs dispersions were checked using standard test processes ASTM D4966, IS 6490, ASTM D5035, respectively. All properties except abrasion were assessed for both warp-wise and weft-wise direction.

4.2.3.7. Antibacterial activity of WPUC-coated PE/C blend fabrics

Antibacterial activities were performed by the standard AATCC 100-2012 method using the *E. coli* and *P. aeruginosa* as gram-negative and *S. aureus* and *B. cereus as* gram-positive as the testing strains.

The bacterial growth (R) reduction on the fabric sample was calculated as:

$$\%\, R = \frac{(B-A)}{B} \times 100$$

Where, R=the reduction rate of bacterial growth, B=the initial number of bacterial colonies and A=the number of bacterial colonies on coated fabrics after contact for 24 hrs.

4.3. Results and discussion

4.3.1. Physical characterization of WPUC dispersions

The outcomes of physical characterization of WPUC dispersion of varying mole ratio of curcumin are shown in **Table 4.4**. Solid contents of the synthesized WPUCs dispersions were found from 30.17% to 33.05 %. The progressive enhancement in the solid weight contents may be due to the increasing amount of curcumin in the WPUC dispersions.

The physical appearance was almost the same milky yellow (except for the WPUC0) in the synthesized dispersions, and their diluted solution showed yellow in color. Here, a yellow

Table 4.4. Properties of the synthesized WPUC dispersions

Properties	WPUC0	WPUC0.1	WPUC0.5	WPUC1
Color & appearance	Milky White	Milky Yellow	Milky Yellow	Milky Yellow
Particle size (nm)	80.1	74.8	58.3	48.2
Zeta potential (mV)	-61.7	-61.4	-52.9	-52.2
Polydispersity index	0.227	0.265	0.149	0.372
Solid content (wt%)	30.17	32.20	32.97	33.05
Storage stability (Months)	> 6	> 6	> 6	> 6

color of dispersion was shown due to curcumin, which is naturally yellow and incorporated as a chain extender into the WPUC backbone. It is shown that the stability of all the developed dispersions (WPUC0 to WPUC1 dispersions) was the same, i.e., they did not display any precipitation over six months. It is possible because of the uniform distribution of curcumin molecules in the polymer chains.

4.3.2. Particle size distribution and zeta potential of WPUC dispersions

The DLS method was used to analyze the particle size distribution of synthesized WPUC dispersions. **Figure 4.4** shows the particle size distribution of the synthesized WPUC dispersions with varying mole ratios of curcumin.

The particle sizes of WPUC dispersions, in the form of hydrodynamic diameter (Dh), were of 80.1, 74.8, 58.3, and 48.2 nm for WPUC0, WPUC0.1, WPUC0.5, and WPUC1, respectively. It is shown that each WPUC dispersion has small particle sizes (d<100nm), and the size distribution was extremely narrow with a PDI of less than 0.5, indicating that each WPUC dispersion was uniform and well-dispersed.

The stability of the WPUCs was also checked with the particle size distribution measurements after 8 months shown in **Figure 4.5**, and negligible changes confirmed the stable form of dispersions. Here, when the curcumin molar ratio rises from 0 to 1 mM, the particle size of WPUCs reduces from 80.1 to 48.2 nm. Such an alteration happened due to the increasing amount of curcumin in the WPUC dispersion. This is indicated to the presence of curcumin lowering the surface tension of the PU dispersion system as hydrophobic in nature, which also promotes fine particle dispersion, inhibits agglomeration, and leads to reduced particle size.

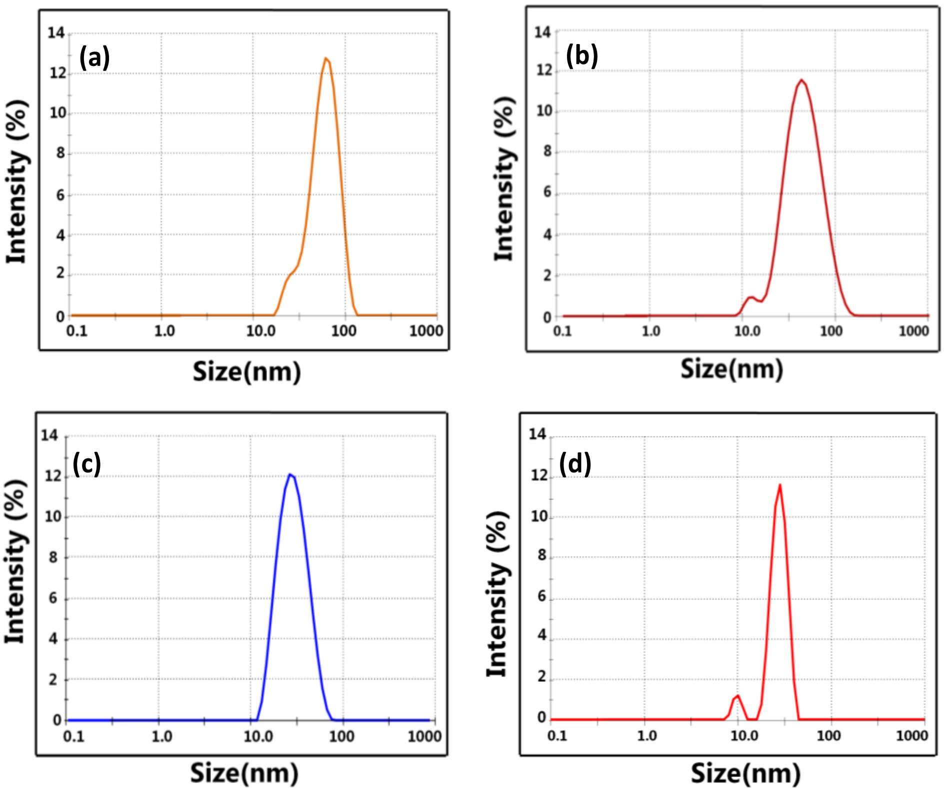

Figure 4.4. The particle size distribution of (a) WPUC0, (b) WPUC0.1, (c) WPUC0.5, (d) WPUC1

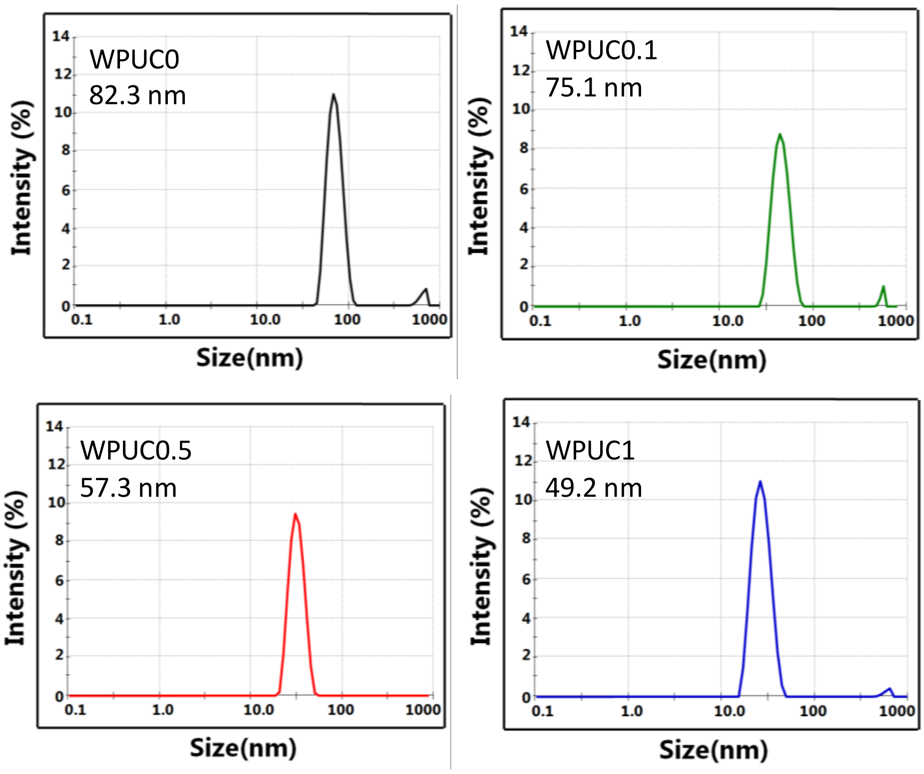

Figure 4.5. Particle size distribution curves of WPUCs dispersion after 8 months period.

The zeta potential is a recognized parameter in colloidal science and is used to assess the stability of colloidal dispersions. For WPUs, a greater than ±30 mV value of zeta potential is generally preferred for better stability, as particles tend to repel each other, preventing agglomeration. Here, the electrostatic repulsion between particles helps to overcome other attractive forces, such as van der waals forces, and keeps the particles dispersed. As shown in the **Table 4.4**, all WPUC dispersions display a zeta potential below than -52.2 mV, indicating stable emulsions. The magnitude of the zeta potential follows the same pattern as the WPUCs particle size. The zeta potential of WPUC0 is -61.7 mV, while that of WPUC1.0 is -52.2 mV. Additionally, the zeta potential of WPUCs decreases with higher curcumin content. Here, WPUC dispersions are electrostatically stabilized by carboxylate ions of neutralized PU; therefore, a stable electrical double layer is formed around the WPUC particle, which hinders the aggregation of particles and leads to higher zeta potential values.

4.3.3. Structural characterization of WPUC films

The ATR-FTIR spectra of bioactive curcumin and synthesized WPUC films are shown in **Figure 4.6**. It is obvious that the spectrum of prepared WPUCs includes some bands that are not present in spectrum of the CO, which confirms the formation of WPUC dispersion.

In **Figure 4.6**, spectrum of curcumin, showed a distinct peak at 3506 cm^{-1} associated with phenolic −OH stretching vibration. The C=O stretching was linked to the absorption peak at 1626 cm^{-1}. The stretching of C=C bonds within the benzene ring was associated with the peaks at 1601cm^{-1} and 1506 cm^{-1}.[41] The bands observed at 1275 cm^{-1} were a result of the C-O bond present in the enol. Furthermore, the bands falling within the range of 960-810cm^{-1} were indicative of out-of-plane bending in C-H bonds and the stretching of aromatic structures.

The ATR-FTIR Spectrum of four different WPUCs is shown in the same **Figure 4.6**. The characteristic peak for NH stretching was clearly visible at 3325 cm^{-1}, and a symmetric CH stretching linked to CH_2 groups was visible at 2924 cm^{-1}. The C=O stretching and NH deformations were associated with the absorption maxima at 1699 cm^{-1} and 1459 cm^{-1}, respectively. At 1031 cm^{-1}, C-O-C stretching has been found. The absence of band associated with phenolic −OH stretching vibration at 3506 cm^{-1} in the synthesized WPUC clearly indicated the insertion of curcumin into the PU chain. All the four spectrums have clearly shown absorption peaks as nearby the same as above.

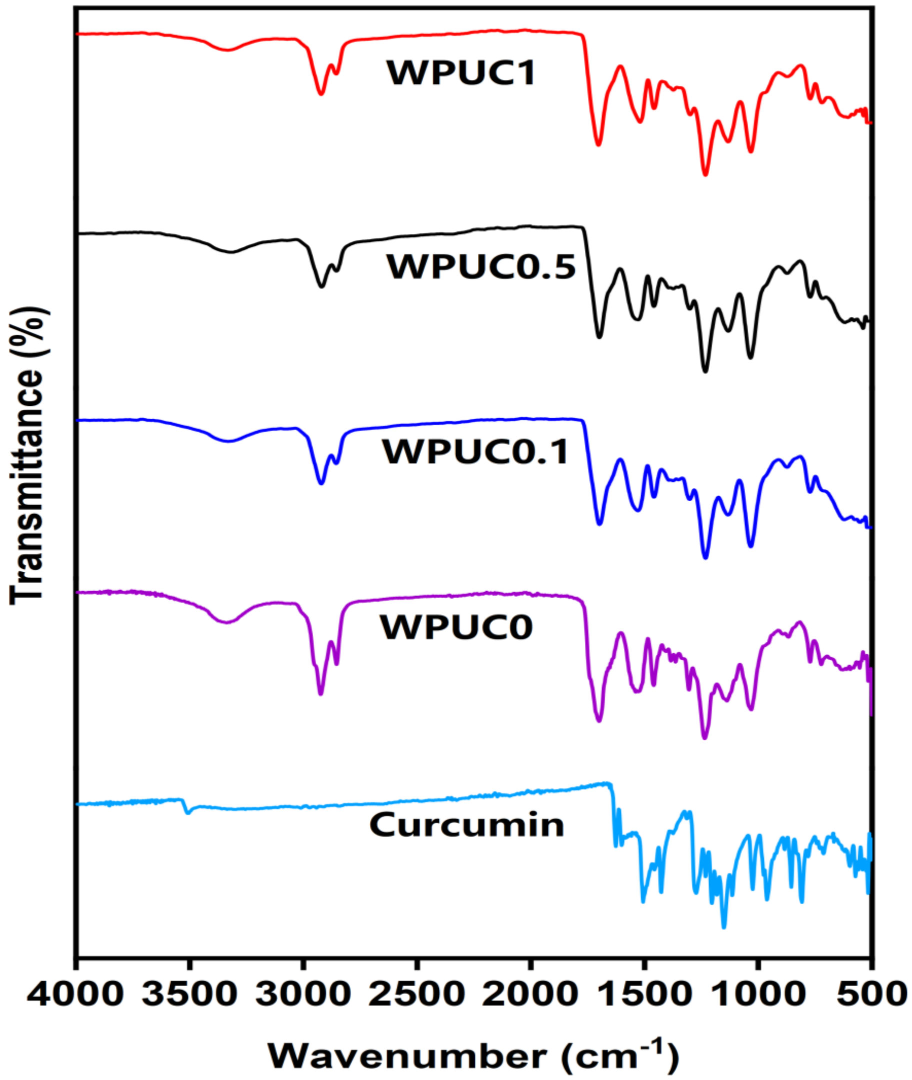

Figure 4.6. ATR-FTIR spectra of curcumin and various synthesized WPUCs

4.3.4. Color fastness evaluation of WPUC-coated PE/C blend fabrics

CO-based WPUCs, synthesized by changing the mole ratio of curcumin, were successfully coated to PE/C blend fabric using the dip coating technique. The effect of washing, light, and rubbing on the color fastness of the WPUC-coated PE/C blend fabric samples has been evaluated using the standard methods applied in the textile studies and results are reported in the **Table 4.5**.

The results from the washing fastness experiment (ISO-1006-C03 (ISO 3)), which encompassed the change assessments on shade and staining of the WPUC-coated PE/C blend fabric samples, were compared to the ratings of uncoated PE/C blend fabric samples. The results clearly revealed that the WPUC-coated fabric samples exhibited significantly improved washing fastness properties compared to the uncoated fabric samples. As per the ratings, the uncoated fabric samples attained shade and staining change ratings of 3. Notably, the fabric samples coated with WPUCs showcased shade and staining change ratings ranging from 4/5 to 3/4 on the grayscale which considered the enhanced resistance against staining and shade change. The improved color fastness to washing performance of the WPUC-coated fabric samples compared to uncoated fabric samples can be attributed to the development of an efficacious and stable WPUC coating layer on the fabric samples.

Table 4.5. Color fastness properties of WPUC-coated and uncoated PE/C blend fabrics

Sample	Color fastness to Washing Rating out of 5		Color fastness to Light Rating out of 8	Color fastness to Rubbing Rating out of 5	
	Stain	Shade-change		Dry	Wet
Uncoated	3	3/4	8	3/4	3
WPUC0	3/4	3/4	8	5	5
WPUC0.1	4/5	4/5	1	5	5
WPUC0.5	4/5	4/5	2	5	5
WPUC1	4/5	4/5	2	5	5

Here, all the WPUC-coated PE/C blend fabric samples consistently demonstrated improved results. This can be credited to the unique structure of WPUCs, which facilitates enhanced hydrogen bonding with the OH groups present in the PE/C-based fabric. Hence, the good interaction between the WPUC and PE/C blend fabric contributed to the enhancement in the washing fastness properties (shown in **Table 4.5**).

The results of the impact of light on the colorfastness of the WPUC-coated and uncoated PE/C blend fabrics assessed through BSI006:1987 technique are presented in **Table 4.5**. All the WPUC-coated fabric samples have shown a light fastness rating in the range of 1 to 2 due to the presence of curcumin. The poor light resistance for the color of the fabric is obviously found because curcumin is a natural yellow dye and very sensitive to light, specifically sunlight. When curcumin is exposed to sunlight, it can undergo photodegradation, causing the color to fade or change. This sensitivity can lead to a reduction in colorfastness to light in PE/C blend fabrics coated with WPUCs.

The color fastness to rubbing of the textile PE/C fabric samples after applying WPUCs by changing the curcumin ratio was assessed using the standard BS1006; NOX 12:1978 techniques (shown in **Table 4.5**). The results demonstrated that WPUC-coated PE/C fabric samples have a reasonable influence on rubbing fastness when compared to the uncoated fabric. Uncoated samples had rubbing ratings of dry 3/4 and wet 3 out of 5, while WPUC-coated fabrics have been shown best rubbing ratings of dry 5 and wet 5 out of 5. Such results clearly demonstrated that all of the WPUC-coated fabrics have shown good rubbing fastness.

4.3.5. Air permeability of WPUC-coated PE/C blend fabrics

The air permeability of the fabric is defined as the rate of air flow passed through a given area of the fabric under a specified pressure difference over a given period of time. The fabric samples were measured for air permeability at a pressure of 100 Pa and 200 Pa. **Table 4.6** shows the results of the air permeability measurements.

It is observed that uncoated fabric is highly permeable due to the presence of more void spaces within the fabric. The complete resistance of air permeation was found at a pressure of 100 Pa. As with the three layers of WPUC polymers coated on the PE/C blend fabric, the formation of a continuous film on the fabric surface was shown at 100 Pa. However, three coating layers were not sufficient to completely resist the permeation of air at an air pressure of 200 Pa and show the air permeability of coated fabric between 166-512 litres/m^2/hrs, which is still considered very low compared to uncoated fabric.

Table 4.6. Air permeability of the WPUC-coated and uncoated PE/C blend fabrics

Sample	Air Permeability (Liters/m^2/hrs.) at 200Pa
Uncoated	728
WPUC0	512
WPUC0.1	342
WPUC0.5	206
WPUC1	166

Here, such air permeation was found due to the formation of microcracking in the coating of WPUC polymers. Here, the number of coating layers was increased to obtain complete resistance to air permeation at 200 Pa, and it was observed with five layers of WPUC coating. Therefore, the WPUC-coated fabrics with the five layers of coating can be suitable for textile applications where high air resistance is required such as industrial filters, tents, sailcloths, parachutes, tarpaulins, etc.

4.3.6. Mechanical properties of WPUC-coated PE/C blend fabrics

4.3.6.1. Abrasion Resistance

Abrasion resistance is the ability of a substrate to withstand wear caused by friction with another surface.[42] **Table 4.7** shows the number of strokes required to abrade the cloth surface at 12 KPa pressure. It can be observed that, at 925 abrasion strokes, the base PE/C blend fabric is damaged. However, even after 10,000 abrasion strokes, the WPUC-coated fabric demonstrates abrasion resistance and was not torn. This indicates that prepared WPUC polymers may significantly improve the abrasion resistance of the studied fabric.

Table 4.7. Mechanical properties of the WPUC-coated and uncoated PE/C blend fabrics

Sample	Abrasion (No. of stroke) 12 kPa Load	Bending modulus (kg/cm^2)	
		Warp-wise	**Weft-wise**
Uncoated	925	126.84 ±2.61	119.45 ±1.44
WPUC0	>10000	1036.52 ±33.17	844.24 ±25.53
WPUC0.1	>10000	1155.20 ± 74.40	788.44 ±70.81
WPUC0.5	>10000	1081.07 ±9.34	830.41 ±11.33
WPUC1	>10000	1192.80 ±9.44	840.52 ±62.66

4.3.6.2. Bending modulus

The bending modulus is an indication of the stiffness of the fabric, a value independent of the dimensions of the strip tested that may be regarded as the ‘intrinsic stiffness’. It is a useful tool to compare the stiffness of fabric of different thicknesses and weights. The bending modulus of prepared samples was evaluated as shown in **Table 4.7**. The bending modulus of uncoated fabric was 126.86 kg/cm^2 and 119.45 Kg/cm^2 in warp-wise and weft-wise directions, respectively. The bending modulus was raised after WPUC coating in the range of 900–1070 kg/cm^2 in warp-wise direction and 665–725 kg/cm^2 in weft-wise direction respectively. The rise in the bending modulus indicates the increase in stiffness of the fabric after coating. This may be due to the penetration of WPUC dispersion within the pores of the fabric and after drying the formation of continuous polymeric film on the surface of the PE/C fabric. Apart from that, it was observed that bending modulus in warp-wise direction for each fabric was higher than in weft-wise direction. This can be attributed to the basic construction of fabric as the fabric is having blend ratio of 67/33 for PE/C blend fabric. The enhanced material stiffness is relevant to various industrial applications such as industrial filters, tents, sail cloths, parachutes, tarpaulins, etc. The increased stiffness falls within a normal range suitable for the intended applications. This increased stiffness is anticipated to enhance the material's performance without any adverse effects.

4.3.6.3. Tensile strength

Tensile strength is the measure of the force needed to break a sample. **Table 4.8** shows the average tensile strength and elongation values along with their standard deviation.

Table 4.8. Average tensile strength and elongation values of the WPUC-coated and uncoated PE/C blend fabrics

Sample	Warp direction				Weft direction			
	Load (N)	SD* (N)	Elongation (%)	SD* (%)	Load (N)	SD* (N)	Elongation (%)	SD* (%)
Uncoated	369.80	22.10	22.90	00.64	281.96	03.15	29.85	02.10
WPUC0	346.32	12.86	19.63	00.84	277.48	29.37	33.58	02.64
WPUC0.1	390.11	32.30	19.55	02.40	278.15	26.35	30.77	02.05
WPUC0.5	364.68	14.76	20.07	01.98	249.39	22.60	31.24	01.75
WPUC1	378.27	09.05	21.41	00.97	285.03	24.26	25.71	02.33

*SD: Standard deviation

The load versus percentage elongation curves for each WPUC-coated and uncoated PE/C blends fabric in warp-wise and weft-wise directions are shown in **Figure 4.7**.

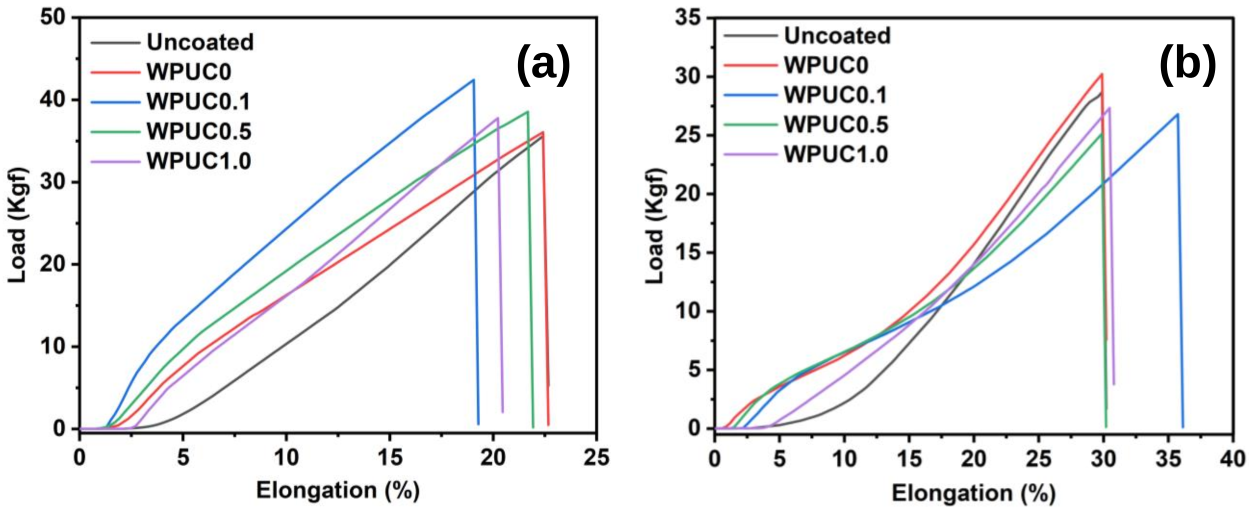

Figure 4.7. Comparison of Load-Elongation curve in (a) warp-wise and (b) weft-wise direction

It can be observed that by treating the base fabric with prepared WPUCs polymers, the tensile strength was initially increased and represented highest strength with WPUCs0.1. However, the further increased in curcumin percentage leads to decrease in tensile strength of the coated fabric. This can be attributed to higher amount of curcumin which makes the material stiffer and if this polymer bound threads tightly within its structure, it results in decline in tensile strength. The same trend was seen in weft-wise directions. Among the coated fabrics, WPUC0.1 shows the highest strength in both directions. It can also be observed that for each fabric, tensile strength is lower in the weft-wise direction compared to the warp-wise direction.

This can be due to a higher number of threads contributing in the warp-wise direction compared to the weft-wise direction, as the set of the fabric is 108×88.

4.3.7. Antibacterial activity of WPUC-coated PE/C blend fabrics

Curcumin is widely recognized as the safest and most potent antimicrobial substance. Moreover, textiles like cotton and wool potentially hinder the growth of microbes by utilizing curcumin.[43] To improve antimicrobial skin ointments and suspensions that offer better wound dressing and skin protection, a blend of curcumin with various antimicrobial agents is used.[44] Earlier studies validated that polyurethanes are biocompatible,[45,46] and the this investigation assessed the antibacterial potential of WPUC polymers based on CO and IPDI after applying on PE/C blend.

The antibacterial investigations of the WPUC-coated and uncoated PE/C blend fabric samples were performed using the selected gram-negative (*E. coli* and *P. aeruginosa)* and gram-positive (*S. aureus* and *B. cereus*) bacteria. Here, each fabric sample was co-cultured with 1 mL of bacterial suspension before enumeration. The results of the assessment are reported in **Table 4.9**, and the visual images are shown in **Figure 4.8**.

It is observed that all the WPUC-coated fabric samples (WPUC0.1 to WPUC1) showed a bacterial inhibition rate of 83.12–99.9999% ($p < 0.001$), compared with blank fabric. Notably, no colony-forming unit (CFU) counts were observed for *E.coli*, *P. aeruginosa*, and *S. aureus* on the WPUC1 sample, suggesting the complete inactivation of the bacteria except for *B. cereus*.

Table 4.9. Antibacterial activity of WPUC-coated and uncoated PE/C blend fabrics

Bacteria	CFU/ml after inoculation on 1×1 cm^2 fabric of each sample								
	Uncoated	WPUC 0	%R	WPUC 0.1	%R	WPUC 0.5	%R	WPUC 1	%R
E. coli	1.28×10^8	1.02×10^8	20.31	2.16×10^7	83.12	2.0×10^5	99.84	1.49×10^5	99.88
P.aeruginosa	2.32×10^7	1.49×10^7	35.77	2.48×10^5	98.93	1.83×10^5	99.21	2.59×10^3	99.98
S. aureus	3.82×10^8	2.39×10^7	93.74	3.62×10^6	99.05	2.42×10^5	99.93	2.94×10^4	99.99
B. cereus	1.24×10^6	2.48×10^5	80.00	1.55×10^5	87.50	1.06×10^5	91.45	2.86×10^3	99.76

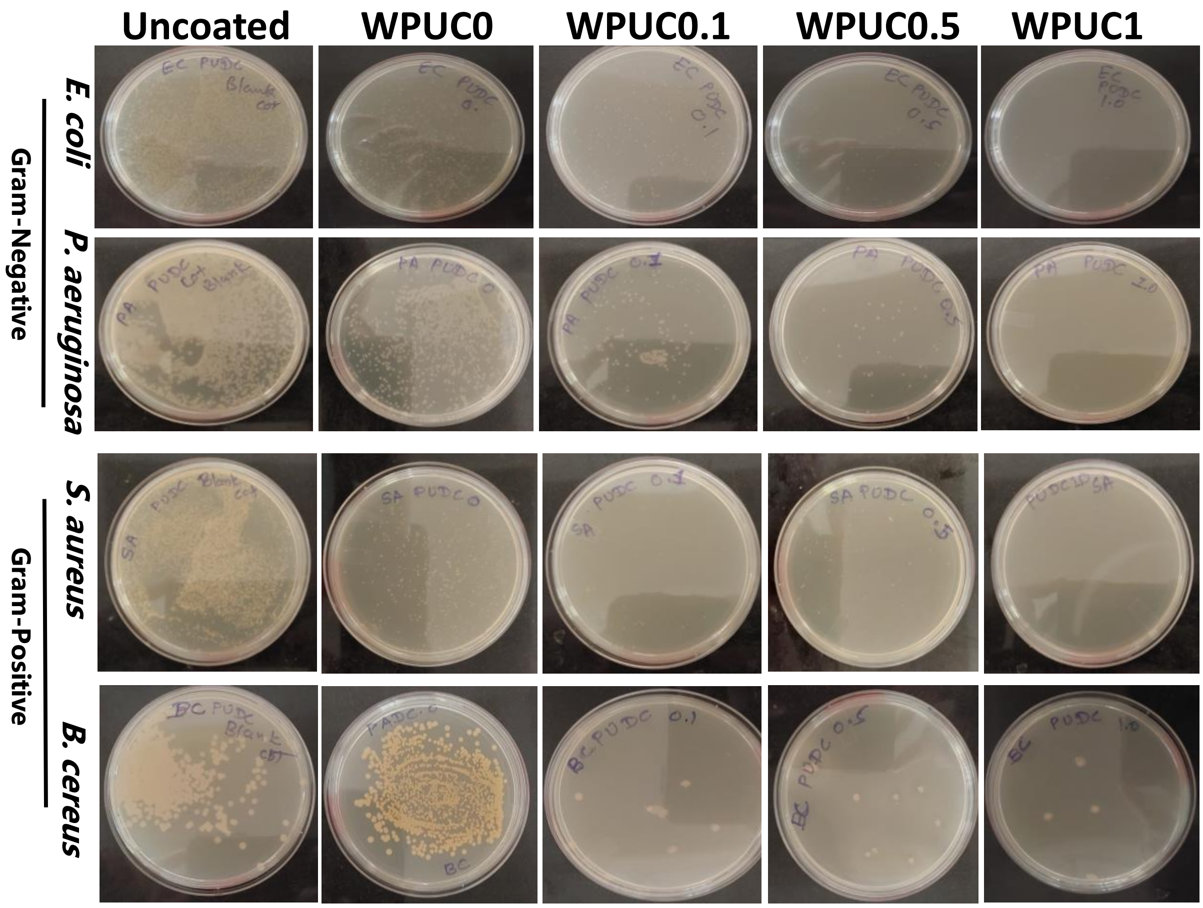

Figure 4.8. Antibacterial activity of the WPUC-coated and uncoated PE/C blend fabrics

Interestingly, the antibacterial effect of WPUC-coated fabric against *E. coli*, *P. aeruginosa, S. aureus,* and *B. cereus* increases with increased curcumin content in WPUC dispersion.[39]

Curcumin may disrupt the integrity of bacterial cell membranes. Bacterial cell membranes are composed of lipids, and curcumin's inherent antibacterial nature allows it to interact with these lipids. This interaction can disrupt the structure and function of the cell membrane, leading to leakage of cellular contents, loss of vital nutrients, and ultimately cell death. This mechanism is thought to be effective against both gram-positive and gram-negative bacteria, as both types of bacteria have cell membranes that can be targeted.

4.4. References

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