Comparative study of coating agents for prevention of fine-dust-induced light transmittance reduction in greenhouse covering materials

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Abstract

Recently, rapidly growing industry and abnormal climate change have generated high concentrations of fine dust. This fine dust settles on greenhouses and hinders photosynthesis of the plants within. In this study, the greenhouse environment was reproduced using fine dust devices, and the fine dust adhesion and washing efficiency were compared. The optimal coating agent was selected by performing a coating experiment to assess the changes in the light transmittance and contact angles of eight greenhouse coatings incorporating different coating agents. The most pronounced adhesion rate was observed in an ion humidification test for $(NH_4)_2SO_4$. The coating agent with Teflon, which exhibited the largest contact angle in this study, had the highest washing efficiency, followed by the coating agent with the highest polydimethylsiloxane ratio using isopropyl alcohol (IPA) as a solvent, and the coating agent with the highest polydimethylsiloxane using water as a solvent. However, the ingredients added to the agents with Teflon or IPA were judged inappropriate for greenhouse use due to environmental reasons. Therefore, the coating agent with the highest polydimethylsiloxane using water as a solvent, which is the most suitable coating agent and satisfies both the washing efficiency and contact angle requirements, is expected to be used as a greenhouse coating agent to prevent light transmittance reduction in greenhouses due to fine dust accumulation

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Introduction

As a result of rapid industrialisation and abnormal climate change caused by environmental problems, high concentrations of fine dust have recently become a frequent occurrence in South Korea. In Seoul, fine dust pollution is a more severe problem than in other major cities in advanced countries (Ministry of Environment [ME], 2017). According to the 'State of Global Air 2016' report released by the Health Effects Institute (HEI) in 2017, the population-weighted annual average concentration of ultrafine dust in South Korea was 29 $\mu g\ m^{-3}$, which is three times the standard recommended by the World Health Organization (WHO, 2006), and the second-highest air pollution level among 35 OECD countries (Jeong and Lee, 2018). Recently, high concentrations of ultrafine dust have been recognised as a severe national environmental problem in South Korea, and emergency reduction measures in response to concentrations of ultrafine dust exceeding 50 $\mu g\ m^{-3}$ per day have been introduced (ME, 2019).

Fine dust directly damages not only the atmosphere and human health but also crop growth. In the context of facility cultivation, Seo *et al*. (2005) previously reported that settling fine dust with 1-10 μm diameter on a greenhouse's outer cladding lowers the supply of natural light inside the greenhouse. In a study comparing unused greenhouse film with greenhouse film exposed to the environment for 89 days, the light transmittance rate decreased by 9.7-11.2% (Jeon *et al*., 2002). In addition, environmental factors, such as fine dust and sand, can cause physical problems to a greenhouse plastic film. Djakhdane *et al*. (2016) indicated that the exposure to sand wind results in a significant decrease in the ultraviolet-visible light transmission, and Abdel-Ghany *et al*. (2016) stated that the shading factor of the net of plastic net-houses might rise with time owing to the dust accumulation on the net texture. Overall, when the photosynthetic photon flux density of the sunlight transmitted through the greenhouse cladding decreases, the photosynthesis efficiency decreases, which delays the required increase in crop temperature (Seo *et al*., 2005), thereby degrading the crop quantity and quality (Challa and Schapendonk, 1984; Cockshull *et al*., 1992; Moon *et al*., 2020).

As an alternative, Kim *et al*. (2003) developed a greenhouse film-covering cleaner that increases light transmittance by removing contaminants that accumulate on the outer cover of the greenhouse film, thereby improving crop growth and marketability. Similarly, Jeon *et al*. (2002) studied a washing method for fine dust removal involving automated washing machines for greenhouse covering materials, focusing on variations in the washing rate. However, considering that 44,528 ha (86.5%) of 51,477 ha of the plastic greenhouses in Korea are small single-span greenhouses, automated washing machines have limited applicability (Ministry of Agriculture, Food and Rural Affairs [MAFRA], 2019). Moreover, the washing experiment performed by Jeon *et al*. (2002) involved only a simple comparison of consumer-level surfactants, with no professional washing solutions being considered. In addition, the anti-soil contamination measures were insufficient.

Another method is to apply a coating agent to the greenhouse to prevent contaminant adherence; however, insufficient research on this method has been conducted. Coatings have various industrial applications, as they can prevent surface destruction and contamination due to various external impacts and maintain a smooth surface. One approach to coating design involves using hydrophobic surfaces, some of which are inspired by nature. For example, the natural surface of the lotus leaf is superhydrophobic, having a micro protrusion structure coated with low-surface-energy hydrophobic wax that minimises the water contact on the surface (Lim, 2012). As dust is attached via a weak force, a self-cleaning phenomenon can be observed on such hydrophobic surfaces, with water droplets rolling dust particles together and easily removing them (Lim, 2012). Water-repellent surface-treatment technology based on this phenomenon is expected to be applied in various industries, *e.g*., for building materials, cosmetics, textiles, and high-performance electronic parts, and to exhibit water repellency, antifouling, and lubrication (Choi *et al*., 2019). As a representative example, water-repellent-coated glass mounted on the front of a vehicle or railway vehicle ensures driver visibility in the event of rain. In addition, by preventing water from adhering to a glass surface, contamination caused by water droplets can be reduced, and contaminant adhesion can be suppressed (Yu, 1996; Chang and Lee, 2011). With this effective coating function, prevention of fine dust and water stains due to moisture or rainfall is expected. Therefore, in the context of greenhouses, a coating agent with suitable functionality should be determined, which can then be incorporated into a greenhouse cladding with a hydrophobic surface to prevent the adhesion of fine dust. For greenhouse management, it is necessary to formulate creative methods, such as applying coatings, which is widely used in many industries, to prevent agricultural plants from getting damaged due to a decrease in light transmittance. In this study, the phenomena through which high concentrations of fine dust attach to the surface of a greenhouse covering material are reproduced. To analyse the fine dust adhesion preventability and washing efficiency of covering material coated with different coating agents, we compared the light-transmittance decrease due to accumulation of fine dust and increase due to the washing process of covering materials. A suitable coating agent was selected to prevent fine dust adhesion and washing efficiency by performing experiments evaluating greenhouse cladding surfaces.

Materials and methods

Application of water-repellent coating material on greenhouse film

Experimental water repellent

The greenhouse surface must be maintained as a hydrophobic surface using a coating agent to prevent dust adhesion for effective greenhouse management. The research process was implemented in four stages, as shown in Figure 1. First, the prepared coating agent was coated on the solid surface of the greenhouse cladding to provide hydrophobicity (Figure 1A).

A total of seven coating experiments were performed using seven different coating agents. Four coating agents (labelled C1-A, C1-B, C1-C, and C1-D) were prepared with 20.0% coating solution at room temperature using isopropyl alcohol (IPA, Junsei Chemical Co., Ltd., Tokyo, Japan) as the solvent. Two coating agents (C2-A and C2-B) were prepared with 20.0% coating solution at room temperature using pure water as a solvent, and one coating agent, C3, was prepared with 0.2% w/w of Teflon AF1600 powder dissolved in a perfluoro-compound FC-40 solution (F9755, Sigma-Aldrich Co., Ltd., St. Louis, Missouri, USA). The coating agent components are listed in Table 1, and the coating

Table 1. Coating agents used in experiments.

Coating agent	Glycolipid (%)	Lipopeptide (%)	Polymer bio surfactant (%)	Polydimethylsiloxane (%)
C1-A	5-10	30-40	10-20	15-20
C1-B	5-10	20-30	30-40	10-15
C1-C	5-10	10-20	50-60	10-20
C1-D	5-10	5-10	10-20	60-70
Coating agent	**Glycolipid (%)**	**Cyclomethicone (%)**	**Polymer bio surfactant (%)**	**Polydimethylsiloxane (%)**
C2-A	1-5	20-30	10-20	30-40
C2-B	5-10	30-40	10-20	20-30
Coating agent	**Composition**			
C3	Fluorinert FC-40 (CAS: 86508-42-1)			

components were selected as the standard of economics or safeness with reliable references. Isopropyl alcohol (IPA) is used as a chemical intermediate and in solvent applications in medicine and industry (Logsdon *et al*., 2000) and has the advantage of being low-cost (So *et al*., 2021). Regarding selecting an optimal coating agent for application to greenhouses some agents incorporate IPA as a solvent; however IPA is a volatile organic compound classified as a harmful atmospheric substance. Volatile organic compounds are carcinogenic substances harmful to the human body; these substances have an odour (Ge *et al*., 2018). Cyclomethicone is a highly hydrophobic solvent (Taylor *et al*., 2002), and its safety has been reviewed on several occasions by the cosmetic ingredient review (CIR) expert panel (CIR, 2022). Polydimethylsiloxane (PDMS) is a hydrophobic material that is widely used to generate superhydrophobic surfaces (Yuan *et al*., 2014). Polymer bio-surfactants are polymer materials (Jung *et al*., 2014), and if a nanostructure forms on the surface of the polymer, a superhydrophobic surface can be made without using expensive equipment (Yoon *et al*., 2019).

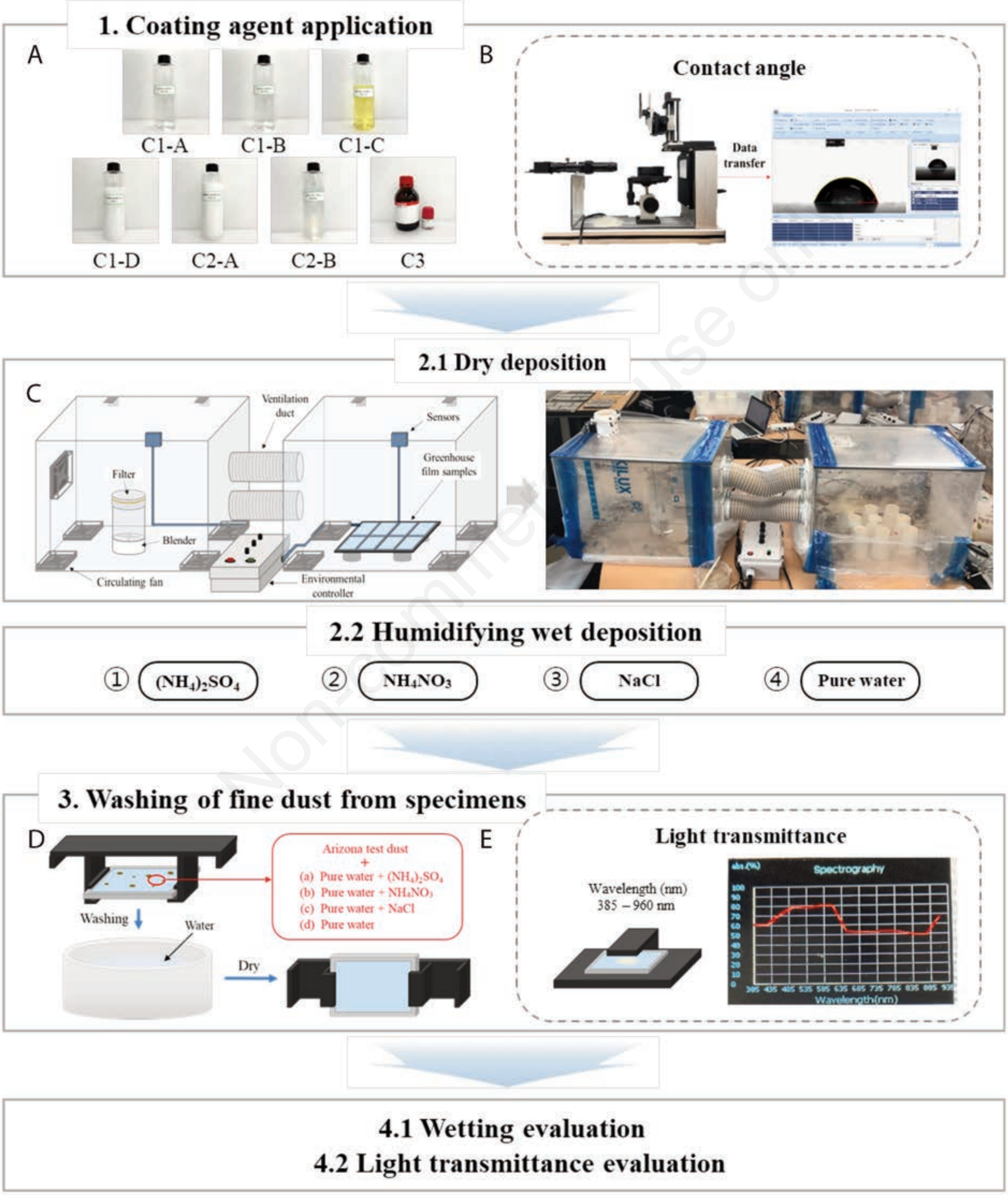


Figure 1. Experiment flow chart.

Lipoptide and glycolipids have the hydrophobicity of biosurfactants (Jung *et al*., 2009), and they can be produced from low-cost materials (Mnif *et al*., 2016; Umar *et al*., 2021). Teflon coating agents are suitable for creating the highest hydrophobic surface; however, they have been steadily regarded as a legal problem with using perfluorinated composites, which are the core inhibitors of Teflon (Kraugud *et al*., 2011). In this study, all the coating agents were prepared by stirring at 1500 rpm for 30 min using a stirrer (HS1-A, LABTron Co., Ltd., Seoul, KOR) in an environment with a constant temperature (20.0-25.0°C) and the air relative humidity (38.0-42.0%).

Water repellent application

A 0.1 mm-thick polyethylene (PE) film (PE film, Sewonfilm Co., Ltd., Goryeong, KOR) was selected to reproduce the greenhouse conditions. Ministry of Agriculture, Food and Rural Affairs (MAFRA) (2014) suggests more than 0.1 mm-thickness regulation of single-span greenhouse. The film is typically used in small single-span greenhouses in Korea (Nam *et al*., 2008), and the use of thin and inexpensive films with approximately 0.1 mm-thickness is economical owing to the summer heat in Korea (Chun *et al*., 2000). To reduce the influence of external factors and facilitate the experiments involving factors such as storage and horizontal maintenance, an acrylic case with 5.0 mm-thickness and dimensions of 65×85 mm^2 was prepared to fix the film. The seven coating agents were then applied to separate specimens reproduced from the greenhouse cladding. Because it is difficult to separate and reinstall film on greenhouses in real farms, a spray coating method was selected from general and accessible coating methods such as dip coating, spray coating, and spin coating. The spray-coating method is also advantageous for coating greenhouse cladding without deformation.

In the coating experiment, an air brush with a 0.3 mm nozzle diameter and a compressor (BBM-P001, Beetle Bug Co., Ltd., Seoul, KOR) were used, and the coating was performed at 2 bar injection pressure. The coating performance was affected by the spray-coating characteristics, *i.e*., the coating agent solvent or the spray distance error between the specimen and air brush. Therefore, to prevent droplets and the flow of each coating agent, the optimum spray distance and spray time were determined through trials. The spray distance was adjusted in 50 mm intervals, the spray time was varied between 5 and 30 s (Table 2), and the results were compared. The specimen and nozzle were fixed vertically in the spraying setup; the coated specimens were dried at constant temperature (20.0-25.0°C) and the air relative humidity (38.0-42.0%) for 48 h. Like this coating process, each coating agent was implemented.

Reproduction of high fine dust concentrations

Fine dust adhesion experiment on greenhouse film

Previous studies analysed the fine dust components of the Korean atmosphere and reported different composition ratios depending on the region and time; however, high ratios of ionic compounds such as $(NH_4)_2SO_4$, NH_4NO_3, and NaCl; carbon materials such as elemental (EC) and organic (OC) carbon; and soil components such as SiO_2 were commonly found (Park *et al*., 2010; Jeon, 2017; ME, 2020). In this study, fine dust components for attachment to the greenhouse specimen were reproduced using Arizona test dust (Powder Technology, Inc.), $(NH_4)_2SO_4$ (Duksan Pure Chemicals Co., Ltd., Ansan, KOR), NH_4NO_3 (Daejung Chemicals & Metals Co., Ltd., Siheung, KOR), and NaCl (Daejung Chemicals & Metals Co., Ltd., Siheung, KOR). The Arizona test dust used in the fine dust adhesion experiment consisted of 77.0% SiO_2, 14.0% Al_2O_3, and 7.0% Fe_2O_3; this composition is mainly used in research on fine dust generated in ground soil (Jokisch *et al*., 2017).

The fine-dust adhesion experiment was conducted in an experimental device in which two sealed acrylic chambers ($600\times800\times600$ mm^3) were connected (Figure 1C); these chambers were labelled Chambers A and B. After coating and drying, the eight specimens were placed in Chamber B at regular intervals and height, and 24.0 g of Arizona test dust was placed in the blender of Chamber A of Figure 1C. A pre-filter (Puricare 360 Filter Ultrafine Filter, Hanguk Filter Co., Ltd., Paju, KOR) was attached to the blender entrance to maintain a constant fine dust size. Following the arrangement of the specimens in the chamber, the blender was operated to spray the fine dust physically, and atmospheric circulation was achieved using five circulation fans installed in each chamber. In this manner, an environment was established in which the experimental fine dust particles of Chamber A were attached to the specimens in Chamber B. Environmental sensors were installed at both ends of the chamber to measure the fine dust concentrations (PM_{10} and $PM_{2.5}$), temperature, and relative humidity. The temperature (20.0-25.0°C) and the air relative humidity (38.0-42.0%) were set equally during the time cycle. Park *et al.* (1997) showed that the light transmittance value of greenhouses exposed to fine dust for approximately 1-2 years decreases to 78.4-69.7%. In our experiment, preliminary experiments were conducted to maintain the LT_3 (light transmittance value when the fine dust and humidification ions were formed) at 70.0-80.0% in our experiment. The adhesion experiment was conducted 12 times, for 24 h at a time, with the Arizona test dust being sprayed for 16 s every 5 min, which was empirically derived by artificially adjusting the spraying time through preliminary experiments. As a quantitative study using an empirical research method (Yoon *et al*., 2015), the experimental time for one experiment was set on a per-day basis

Table 2. Spray-coating method parameters.

Coating agent	Solvents	Spray distance (cm)	Spray time (s)	Dry time (h)
C1-A	IPA	30	20	48
C1-B		20	20	48
C1-C		25	20	48
C1-D		25	30	48
C2-A	Water	40	5	48
C2-B		40	5	48
C3	-	25	10	48
Untreated	-			

(24 h) to repeat the experiment several times and as efficiently as possible. As a result, The LT_3 result values of the actual data were 75.18%±1.39%.

Ion humidification experiment to fix fine dust

In the ion humidification experiment, the phenomenon in which fine dust adheres to a greenhouse surface in the form of a wet drop through accumulated moisture or rainfall was implemented. For this experiment $(NH_4)_2SO_4$, NH_4NO_3, and NaCl, which were dissolved in water and ionised, were selected from the various experimental fine dust components. To determine the greenhouse attachment characteristics of each component, an ion humidification test involving four cases was performed; the cases are detailed in Table 3.

The procedure was as follows. After the fine-dust adhesion experiment was completed, the eight samples with fine particles attached were immediately moved to the ion humidification chamber, placed in a sealed plastic box chamber (600×400×300 mm^3), and humidified for 20 min. This experiment was conducted for each ion configuration listed in Table 3. Because three ion humidification experiments were conducted for each case, twelve experiments were performed.

Washing experiment to remove fine dust from greenhouse film for greenhouse use

A washing experiment was conducted to remove the fine dust attached to the greenhouse specimens. Hence, the washing efficacy according to the coating agent and ionic solution were compared. Pure water was used in the washing experiment because it is the most accessible solvent and is commonly used on domestic farms. The only chemical reaction was considered in the washing experiment except for the physical washing method to compare the fine-dust adhesion and cleaning effects by coating agent, and thus the experiment was conservatively set. Therefore, the situations in which fine dust is physically removed were excluded, such as washing the dust by spraying water directly through a hose or removing the dust by wind or raindrops. The contaminated specimen was immersed twice for 5 min in a container containing the washing liquid in the experiment. After the washing, the specimen was vertically positioned so that the fine particles could roll off in the surface water and dried in an enclosed space for 24 h (Figure 1D).

Coating performance evaluation based on greenhouse film analysis

Wettability test

Two evaluation methods were used to evaluate the performances of all the seven coating agents. First, to understand the surface characteristics of the cladding specimen, the surface wettability was measured. The coating surfaces were classed as superhydrophobic, hydrophobic, or hydrophilic, with their wettability being evaluated based on the contact angle between the surface and water droplets formed by dropping water on the coating surface (Wenzel, 1936). Note that when the contact angle exceeds 150° and is in the range of 90-150°, or less than 90°, the surface is referred to as superhydrophobic, hydrophobic, or hydrophilic, respectively (Li *et al*., 2007) (Figure 2). To realise a superhydrophobic surface, a pre-treatment process is first required to form a nano-projection surface. However, it is challenging to implement a professional pre-treatment process for the greenhouse cladding materials used in general farms. Therefore, this study focused on excluding this process and reproducing a surface close to hydrophobic through coating agent application.

The procedure was as follows. After applying the coating agent

Table 3. Ion humidification experiment cases.

Case	Experimental dust	Ion solution components
1	24.0 g Arizona test dust	$(NH_4)_2SO_4$ 20.0% + pure water 80.0%
2	24.0 g Arizona test dust	NH_4NO_3 20.0% + pure water 80.0%
3	24.0 g Arizona test dust	NaCl 20.0% + pure water 80.0%
4	24.0 g Arizona test dust	Pure Water 100.0%

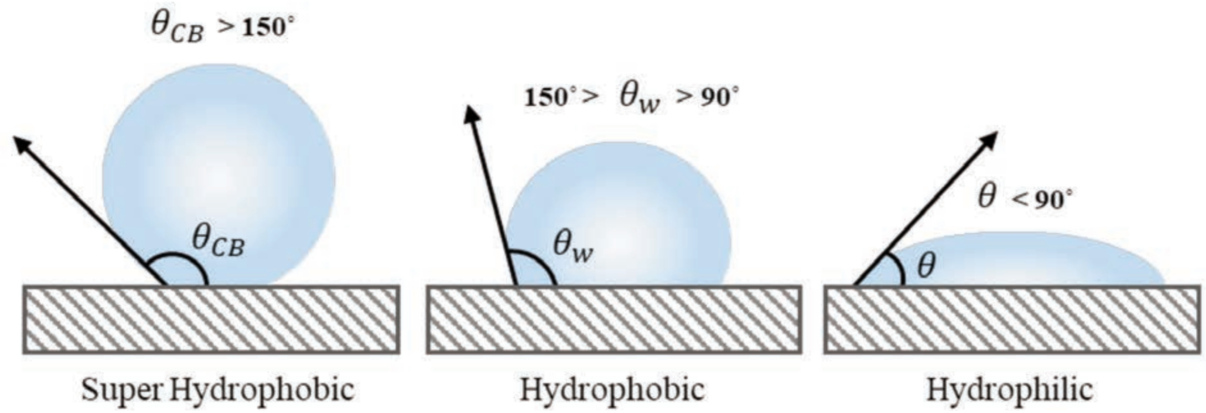


Figure 2. Surface properties depending on contact angle.

to a greenhouse cladding specimen and drying for 48 h, the static contact angle between the specimen surface and water was measured (Figure 1B). The contact angle measurement experiment was conducted by dropping 5.0 μL, 2.0 mm-diameter purified water droplets on the specimen surface using a 100.0 μL needle. All contact angle measurements were conducted in an environment with constant temperature and humidity.

Light transmittance evaluation

To observe the surface changes of the specimens contaminated by fine dust and the effects on light transmittance, the light transmittance was measured using a sensor (AS7265x, ams Co., Ltd., Premstätten, AT) mounted on the transmittance measurement device, and the sensor was successfully used (Tran *et al*., 2020; Botero-Valencia *et al*., 2021; Leon-Salas *et al*., 2021). In the light-transmittance measurement device, the rest of the components, except for the measurement sensor AS7265x, are composed of the components that input/output and visualise data. This device is registered as a patent (KOR. Patent No. 1020210154456, 2021). Light transmittance values were recorded for each specimen at the following four stages: when the polyethylene film (LT_1) was untreated, following the application of the coating agent (LT_2), when the fine dust and humidification ions were formed (LT_3), and after washing (LT_4). As the measured values, light-transmission-reduction rate after coating (LT_{coat}), following fine dust adhesion (LT_{attach}), and increased rate after washing (LT_{wash}) was obtained, as defined in Equations (1), (2), and (3), respectively. For light transmittance measurement, each specimen surface was divided into nine regions, and the average of the nine values obtained for these regions was input as the light transmittance of the overall specimen (Figure 3). The visible-light wavelength band (380-780 nm) was divided into 25 nm intervals, and the light transmittance was measured based on the amount of light detected before and after passage through the specimen for each wavelength band. The visible band was selected to present the physical characteristics of the greenhouse film by evaluating the light-transmittance value. The average of the total wavelength *versus* the light transmittance was defined as the measurement value of the corresponding measurement point.

$$LT_{coat} = \frac{LT_1 - LT_2}{LT_1} \times 100\ (\%) \qquad (1)$$

$$LT_{attach} = \frac{LT_2 - LT_3}{LT_2} \times 100\ (\%) \qquad (2)$$

$$LT_{wash} = \frac{LT_4 - LT_3}{LT_3} \times 100\ (\%) \qquad (3)$$

Results and discussion

Comparison of surface hydrophobization properties according to a coating agent

Figure 4 shows the surface wettability evaluations performed by dropping purified water on the coated specimens after 48 h of drying. Eight specimens were simultaneously tested for each coating agent, and the experiment was repeated a total of 12 times; thus, 12 contact-angle data points were obtained per coating agent specimen. The measured result distribution for all experiments was as follows: C1-A (99.50°±1.33°), C1-B (101.86°±2.04°), C1-C (98.38°±1.73°), C1-D (96.13°±1.94°), C2-A (99.50°±1.28°), C2-B (63.13°±2.52°), C3 (106.13°±2.51°), and Untreated (81.06°±2.80°), at a 95% confidence level. Note that 'Untreated' refers to a specimen with no coating agent. Further, implementation of a superhydrophobic surface with a coating angle of 150° or higher was limited as a special surface was required. Overall, C3 yielded the most hydrophobic surface; C2-B yielded the lowest contact angle and was, therefore, hydrophilic; and Untreated also exhibited a hydrophilic surface with a contact angle of less than 90°. Considering the confidence interval at a confidence level of 95%, the average contact angles and error intervals of the other coating agents, *i.e*., C1-A, C1-B, C1-C, C1-D, and C2-A were measured to be 99.08°±0.93°. It was determined that the small deviation of 0.93° indicated similar contact angles for each of these coating agents.

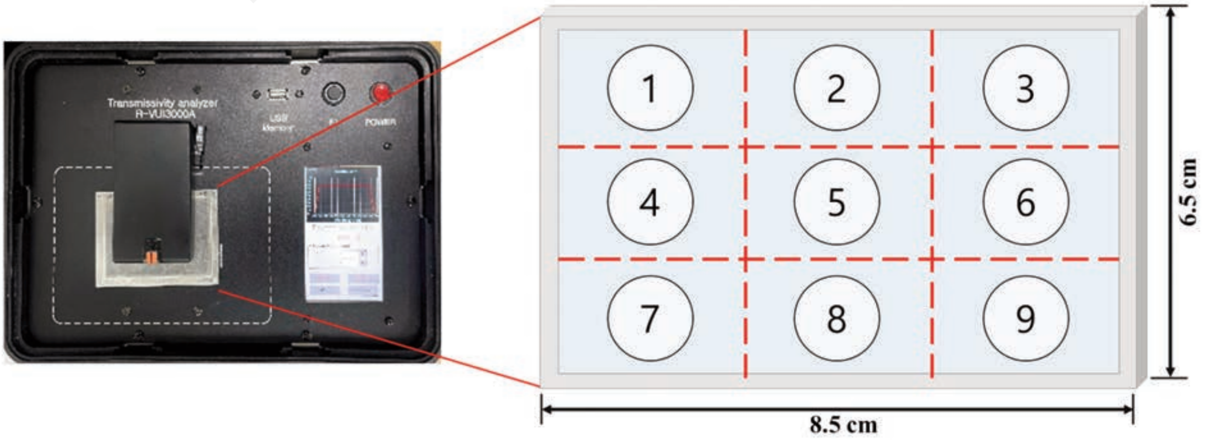
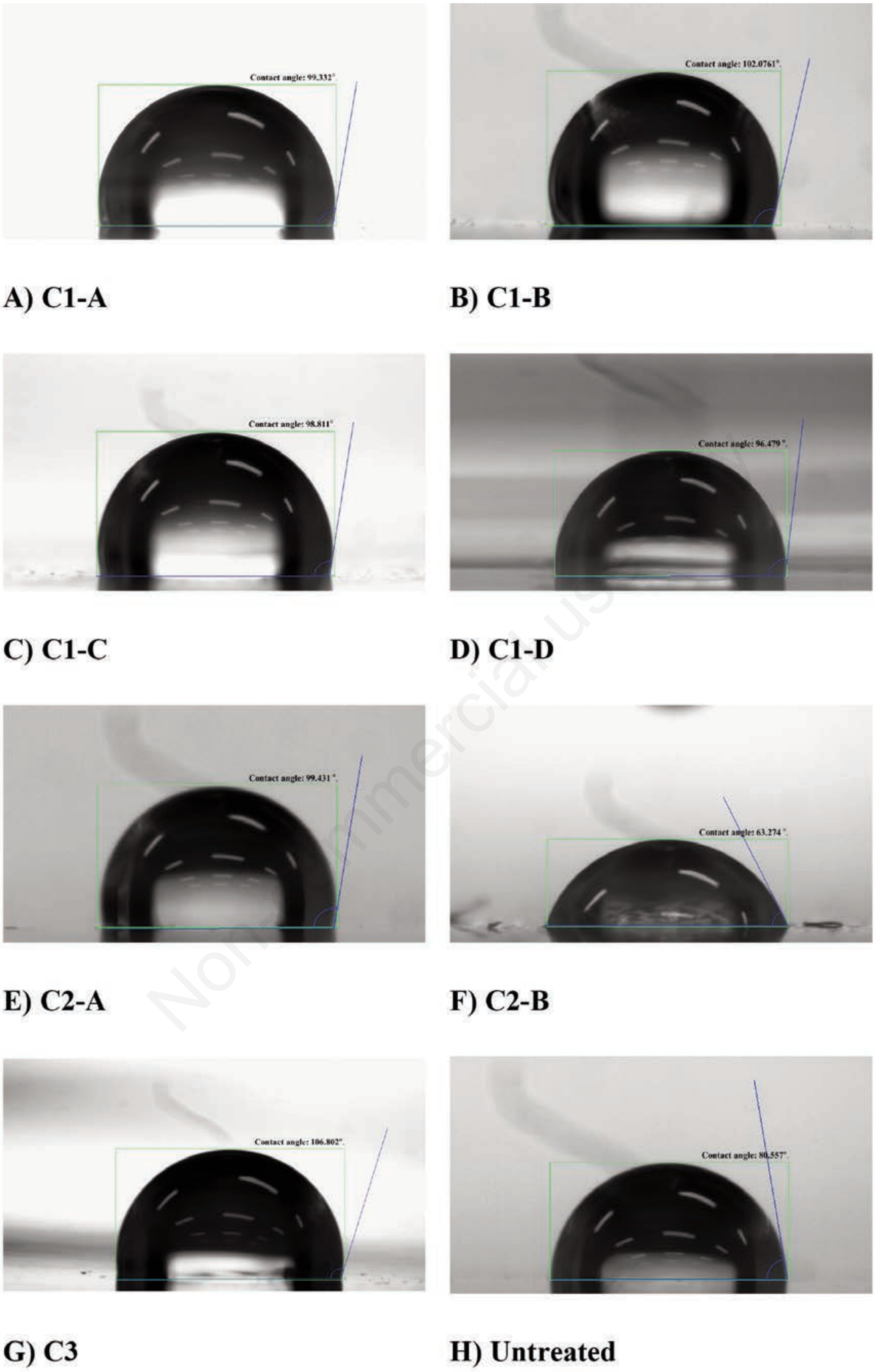


Figure 3. Light transmittance measurement method.



A) C1-A

B) C1-B

C) C1-C

D) C1-D

E) C2-A

F) C2-B

G) C3

H) Untreated

Figure 4. Contact angle results for seven coating agents and untreated material.

Comparison of light transmission reduction

To evaluate light transmission reduction after coating, the light transmission of the untreated PE film and the coated film was compared with twelve specimens for each of the seven coating agents at a 95% confidence level. The LT_{coat} results were in the following: C1-A (–0.005%±0.004%), C1-B (–0.005%±0.004%), C1-C (–0.006%±0.006%), C1-D (–0.005%±0.006%), C2-A (–0.005%±0.003%), C2-B (–0.005%±0.004%), C3 (–0.003%±0.002%). When the coating agent was applied, the change in light transmittance was slight, and the light transmittance increased. Therefore, it indicates that the light transmittance does not decrease even with these coating agents. Figure 5 shows the light-transmission reduction rate data (determined from the light transmission behaviours before and after fine dust adhesion) obtained from the specimens with fine dust and based on the fine dust adhesion and ion humidification tests. In accordance with the cases and conditions listed in Table 3, 12 experiments were conducted (three experiments for each of the four humidification ions); the LT_{attach} values presented in the graph are the average values for each case. Before fine dust adhesion, the average light transmittance value of 96 coated specimens was 89.85%±0.11%, exhibiting a slight deviation. The LT_{attach} results were in the following order: Case 1: $(NH_4)_2SO_4$ 20.0% + pure water 80.0% (36.82%±3.32%) > Case 2: NH_4NO_3 20.0% + pure water 80.0% (25.32%±1.50%) > Case 3: NaCl 20.0% + pure water 80.0% (22.31%±1.00%) > Case 4: pure water 100.0% (18.31%±1.99%), as shown in Figure 5. When ions containing $(NH_4)_2SO_4$ were applied, a large light transmittance reduction rate following fine dust adhesion was observed. In contrast, the lowest light transmission reduction after adhesion was obtained when ions were applied using pure water. Therefore, the most prominent reduction in the cladding light transmittance occurs when the $(NH_4)_2SO_4$ humidifying ion component is attached to the surface of the cladding in the form of a wet drop.

Comparison of light transmittance after washing according to a coating agent

Figure 6 shows the light transmission increase rates after the fine dust was washed from the specimens for each of the four ion solution components. From Figure 6A, for the case of ion humidification with $(NH_4)_2SO_4$, the washing efficiency was in the following order: C3 (57.60%) > C2-A (51.64%) > C1-D (50.37%) > C1-A (43.56%) > C1-B (40.38%) > C1-C (33.29%) > Untreated (28.96%) > C2-B (25.10%). Thus, C3 yielded the highest fine dust washing efficiency, followed by C2-A and C1-D. The lowest washing efficiency was observed for the coating film to which C2-B was applied. Untreated exhibited the next-lowest washing efficiency. Figure 6B shows the washing efficiency results for the case of ion humidification with NH_4NO_3; the order was C3 (24.63%) > C2-A (21.88%) > C1-D (21.21%) > C1-B (17.68%) > C1-A (15.37%) > C1-C (14.51%) > Untreated (12.26%) > C2-B (6.01%). The lowest washing efficiency was observed for the coating film to which C2-B was applied, and untreated exhibited the next-lowest washing efficiency. Except for C2-B, the differences in the fine dust washing efficiencies for the other coating agents were significant. Figure 6C shows the washing efficiency for the NaCl humidification ion case; the order was C3 (18.40%) > C1-D (15.20%) > C2-A (13.01%) > C2-B (10.26%) > C1-B (10.19%) > C1-A (9.4%) > Untreated (7.67%) > C1-C (5.57%). As for the previous two cases (Figure 6A and B), the coating film coated with C3 exhibited the highest fine dust washing efficiency, followed by C1-D and C2-A (in different orders). The coating film to which C1-C was applied exhibited the lowest washing efficiency, and Untreated yielded the next-lowest washing efficiency. Except for C1-C, the differences in the fine dust washing efficiencies for the other coating agents can be evaluated as significant. Figure 6D shows the washing efficiency for pure water; the order was C3 (6.00%) > C1-D (3.96%) > C2-A (1.67%) > C2-B (0.80%) > C1-A (0.62%) > C1-B (0.56%) > C1-C (0.49%) > Untreated (1.76%). Again, C3 had the highest fine dust washing efficiency, followed by C2-A and C1-D. The lowest washing efficiency was observed for C2-B, with Untreated exhibiting the next-lowest efficiency. The overall washing-efficiency distribution pattern indicated high washing efficiency in the order of Case 1, Case 2, Case 3, and Case 4, similar to the light transmission reduction rate results after fine dust adhesion. Finally, as shown in Figure 6E, C3 exhibited the highest washing efficiency at 26.66%, followed by C1-D and C2-A at 22.69% and 22.05%, respectively. Compared to untreated, the results for C1-A and C1-B were higher by only 4.58% and 4.27%, respectively, making it difficult to determine whether those coating agents yielded superior washing effects. Because C1-C exhibited similar washing efficiency to Untreated, it was determined to be ineffective as a coating agent to prevent fine dust adhesion. Finally, C2-B exhibited lower washing efficiency than untreated; therefore, its effectiveness as a coating agent is limited.

Coating-agent selection through film surface evaluation

The cladding surface wettability and light transmittance were examined to evaluate the coating performance of the different coating agents for the greenhouse cladding. Of the eight considered cases, C3 yielded the most pronounced hydrophobic surface, with a contact angle of 106.13°±2.51°, whereas C2-B had the most hydrophilic surface, with the lowest contact angle of 63.13°±2.52°. In terms of washing efficiency based on the resultant light transmittance, the highest LT_{wash} of 26.66% was obtained for the coating material with coating agent C3; the lowest of 10.54% was obtained for C2-B. Thus, the surface wettability and light transmittance results coincide. However, considering the relationship between surface wettability and washing efficiency for the remaining coating agents, *i.e.*, C1-A, C1-B, C1-C, C1-

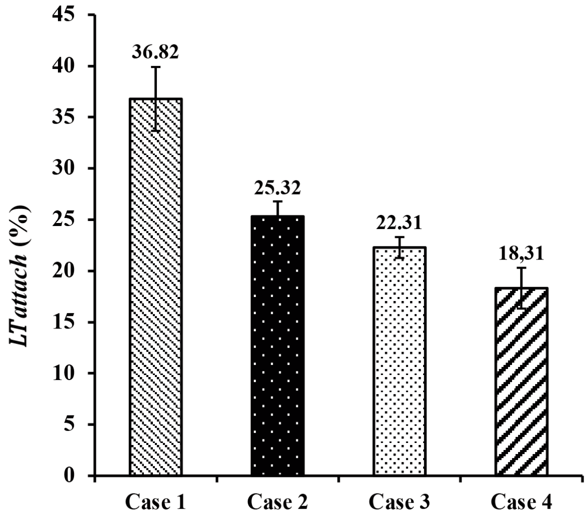
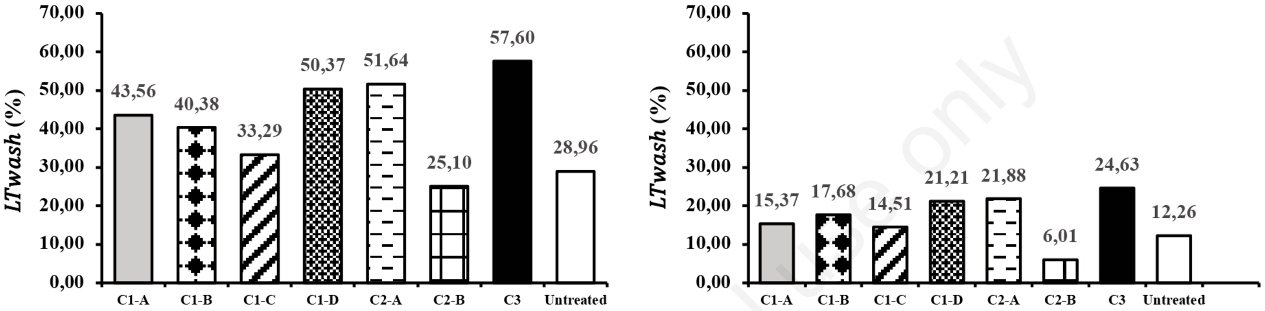


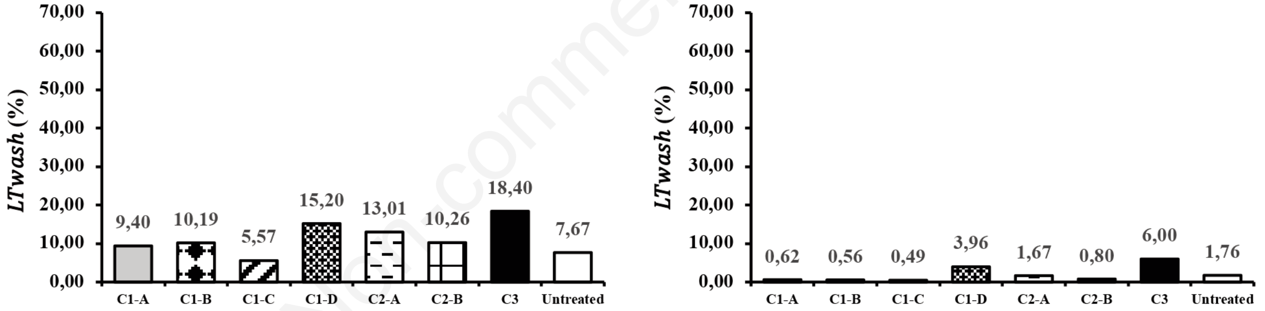
Figure 5. Light transmittance reduction of the fine dust adhesion experiment with humidification ion on greenhouse film according to each case in Table 3.

D, and C2-A, there is a limit to this association as these agents yielded similar contact angles of 99.08°±0.93°. Overall, a comparison of the clear differences in washing efficiency reveals that coating agents C3, C1-D, and C2-A had the most significant performance in all 12 experiments.

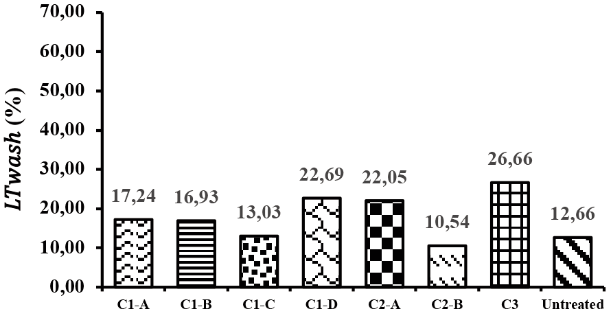
As mentioned earlier, C3 and C1-D contributed to forming a high hydrophobic surface, but these coatings have a bad environmental impact. Because in the case of IPA of C1-D environmental pollution has become an increasingly severe problem, the emission allowance standard of the volatile organic compound has recently been strengthened for workplaces using organic solvents since 2005 (Byun *et al*., 2009). These substances may harm farmers not only through agricultural plants but also through the atmosphere (Korea Optical Industry Association, 2006). In addition, in the case of C3, the compounds raise the incidence of diabetes and high blood pressure, cause infertility, and may have side effects for farm applications (Choi and Lee, 2017). Furthermore, it would be difficult for typical farmers to directly apply C1-D and C3 because they would not have the necessary engineering knowledge or appropriate manufacturing environments to dissolve and apply IPA or Teflon powder directly. Therefore, C2-A was identified as the most appropriate coating agent because it exhibited good coating and washing performances in this study and is practically easy to apply on farms using water.



(A) $(NH_4)_2SO_4$ (B) NH_4NO_3



(C) NaCl (D) Pure water



(E) Total

Figure 6. Light transmittance recovery of greenhouse film following washing with water according to wet-deposition ion solution components.

Conclusions

In this study, seven different coating agents were evaluated for application to the surface of a greenhouse covering material to minimise the adhesion of fine dust. Following the coating, the largest and smallest contact angles were obtained for C3, Teflon, and C2-B with the highest cyclomethicone ratio, respectively, indicating hydrophobic and hydrophilic surfaces, respectively. Fine-dust adhesion and ion-humidification tests obtained the highest fine-dust-collection rate for $(NH_4)_2SO_4$. In the fine-dust washing experiment, C3 exhibited the highest washing efficiency, followed by C1-D and C2-A, with the highest polydimethylsiloxane at similar levels, regardless of the ion solution components. However, C3, a Teflon coating agent, and C1-D containing IPA are harmful to both crops and the human body. As a result, the water-soluble coating agent C2-A, which can prevent decreased light transmittance of covering material, is applicable as an eco-friendly greenhouse coating agent with high accessibility to farmers.

It should be noted that a limitation of the present study is that various proportion compositions of coating agent components were not tested. In addition, because the size of the specimen was small and the number of specimens was not large, it was difficult to completely control the temperature, humidity, and concentration of the fine dust in the environment. Another limitation of our implementation is that hydrophobic and hydrophilic surfaces were considered, whereas superhydrophobic surfaces were not considered. Therefore, future research is required to determine the optimal concentration by comparing various coating agent components and to enable continuous management by applying coating agents even after removing the attached fine dust.

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