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Article

The Effect of Water-Based Primer Pretreatment on the Performance of Water-Based Inkjet Coatings on Wood Surfaces

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Abstract: Wood surface staining suffers from volatile organic gas (VOC) emissions and uneven staining at knots, and these environmental and decorative performance issues are the main restrictions in the application of wood products, indoors and outdoors. Herein, the method of wood-based panel surface staining is presented for improving environmental and decorative performance using environmentally friendly water-based inks, water-based primers, and digital inkjet coloring technology. The wood-based panels' dye coatings were prepared with oak plank as the sample substrate, a one-component water-based primer as the interfacial adhesive, and a water-based ink as a coating agent. The application amount of water-based primer was 15 g per square meter, applied twice by a roller, and the coating thickness reached approximately 20 μm. The influence of the one-component water-based primer on the interfacial properties of water-based inkjet coatings was investigated via Fourier-transform infrared (FTIR) spectroscopy, a video contact angle analyzer, and environmental scanning electron microscopy (SEM). The results showed that the one-component water-based primer connected the plain board to the inkjet-printed coating. The addition of a water-based primer coating reduced the contact angle of the wood surface from 41.69° to 37.28° and increased wettability. This helped enhance the adhesion of the water-based inkjet coating, and the primer treatment in the semi-closed state covered the scar defects of the plain board while preserving the path of grain holes on the wood surface. With image editing and inkjet dyeing, the surface of the oak plank obtained a uniform staining effect on the primer coating while maintaining the original natural pore texture of the wood. This study proves that a one-component water-based primer pretreatment process for water-based inkjet printing coatings on wood surfaces has excellent modification ability and interface adhesion. It provides a feasible method of color modification for artificial panel surfaces.

Keywords: one-component water-based primer; oak plank; water-based ink; inkjet printing

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1. Introduction

Wood is a natural, inhomogeneous, porous material with high permeability [1], which is closely related to wood staining. However, wood staining has become the primary research trend to meet the growing demand for the indoor coloring of wood-based products [2,3]. Traditional wood staining includes deep staining and surface staining. Deep staining mainly uses synthetic dyes, which act directly on the cell walls of the wood fibers from the exterior to the interior. Although the dye uptake and dyeing effect are good, many inorganic salts and color-fixing alkalis are required during this process, which produces a large volume of waste liquid that pollutes the soil and waterbodies [4,5]. Surface dyeing is a spraying, roller coating, or drenching method to treat the surface of wood products. For example, the oak board is a typical hardwood manufacturing wood product. It has a firm texture, a beautiful grain with a surface distribution of a large number of uneven grain holes, natural scars often of different shapes, and uneven wood color caused by early and late wood. However, the method of dyeing has limitations: color penetration is not uniform; there are defects in the modification; and the color variety is limited, affecting the wood aesthetics. These methods struggle to meet the market demand for wood products with rich colors and exquisite patterns. In this context, digital inkjet printers can be used to paint complex wood grain images or other high-quality visual effects directly onto wood substrates. This rapid method creates less waste, may reduce production costs, and may improve dyeing efficiency and final inkjet quality [6].

In recent years, newly developed digital inkjet printing methods have been applied in the wood industry [7,8]. This technology is a noncontact method that enables digitally controlled injections of tiny ink droplets through a printhead into a specified location onto a substrate, accurately depositing a precise amount of ink to create an image [6]. Based on the nature of the inkjet ink, it can be divided into UV ink, solvent-based ink, and water-based ink. The curing mechanism of UV ink is ultraviolet curing, which forms a solid film through cross-linking and polymerization. However, if the UV ink is not sufficiently cured, toxic materials may migrate from the coating surface [9], which can be hazardous to the worker's health in the production process. The solvent-based ink has an organic solvent or solvent-based polymer film-forming agent as a carrier. The solvent is evaporated by heating and drying, producing volatile organic substances, which are wafted into the air and affect human health. Water-based ink is a "green" material that is mainly prepared with water as the solvent, whose mass fraction is approximately 70% [10,11]. It is mainly through infrared light irradiation that the water evaporation takes place, leaving the ink composition dry knot fixed on the substrate surface. The production and use of the process significantly reduce VOC emissions and reduce the solvent odor residue on the surface of the printed coating. Therefore, water-based ink is more environmentally friendly than UV ink and solvent-based ink, which accounts for a significant advantage [12].

While environmentally friendly water-based inks can replace other inks, they suffer from slow drying and poor adhesion [13,14]. Poor ink–substrate adhesion is due to water-based ink's inherently high surface tension. Currently, there are two ways to solve the poor adhesion of water-based inks to wood: change the ink formulation/modification or treat the substrate surface. Ink modification improves the printing performance by adding a small amount of additives [15]. The preparation of high-quality inks is technically demanding. The ink formula should be tailored to match the substrate, which increases the complexity of the process and may waste ink. Therefore, surface treatment represents a new method to optimize printing performance [16,17]. This is fundamentally accomplished through wood surface modification, which narrows the surface energy difference between the water-based ink and the wood substrate to obtain good adhesion, strong abrasion resistance, high stability, and faster drying [18,19]. However, there are few studies on applying water-based ink to the surface treatment of wood substrates.

In this paper, we investigated the performance of a waterborne inkjet dye coating on a wood surface. The purpose was to provide excellent interfacial bonding properties and decorative qualities in an environmentally friendly coating. A one-component waterborne primer was used as a "bridge" to promote the binding force between the waterborne ink and oak plank. The primer treatment in the semi-closed state covered the scar defects of the plain boards while also preserving the path of grain holes on the wood surface so that after inkjet dyeing, the oak planks retained the natural texture of wood, which allowed for the study of the better adhesive and decorative properties of the waterborne wood coating products.

2. Materials and Methods

2.1. Materials, Equipment and Software

The experimental substrate was selected from oak planks (dimensions: 10 cm × 40 cm × 1 cm; air dry density: 0.75 g/m^3; moisture content: 8%). The one-component waterborne polyurethane resin primer was provided by Jiangsu Haitian Technology Co., Ltd. (Jurong, China), and its composition is shown in Table 1. The 5-color CMYKW water-based inks (cyan, magenta, yellow, black, and white) (HONGSAM H5-D310) came from Nanjing Leili

Digital Technology Co., Ltd. (Nanjing, China). The scanned white oak wood grain image was used for the digital image (format: TIF; resolution: 300 dpi; size: 10 cm × 40 cm).

Table 1. Composition of one-component waterborne primers.

No.	Experimental Materials	Molecular Formula
1	H_2O	H_2O
2	Waterborne polyurethane resin	
3	PH regulator	-
4	Defoamer	-
5	Propylene glycol	$C_3H_8O_2$
6	Wetting agent	-
7	Dispersant	-
8	TiO_2	TiO_2
9	Thickening agent	-
10	Acrylic lotion	$C_3H_4O_2$
11	Anti-settling agent	-
12	Film-forming aids	-
13	Foam inhibitor	-
14	Fungicide	-

Water-based inkjet digital printing equipment (E1613) was provided by Nanjing Leili Digital Technology Co., Ltd., equipped with three Epson I3200A1 printheads with a resolution of 360 dpi. The optical contact angle instrument (Thetat200) was obtained from Sweden Bioin Technology Co., Ltd. (Shanghai, China). The optical microscope (CX23LEDRFS1C) was purchased from Olympus (Guangzhou) Industry Co., Ltd. (Guangzhou, China). The environmental scanning electron microscope (FEI, Quanta200) and infrared spectrometer (VERTEX80V, Brooke Spectrometer, Karlsruhe, Germany) were borrowed from the Advanced Analysis and Testing Center of Nanjing Forestry University.

We used RIP software (Maintop PRINT) to interpret the Photoshop files and convert them into raster dot-matrix data recognizable by the printing equipment. Graphs were drawn using Adobe Illustrator 2020 software and Origin 2022 software.

2.2. Description of Roller Coating Process of Water-Based Primer

To optimize the coating performance of the water-based ink spray-printed on the oak plank substrate, we set up three samples for experimental analysis: plain board (i.e., untreated oak plank, hereafter referred to as plain board); water-based primer roller coating; water-based primer and water-based inkjet printing.

The water-based primer and roller coater were provided by Jiangsu Haitian Technology Co., Ltd. Figure 1 shows the process of the film formation mechanism of a one-component water-based primer [20]. The film-forming process did not need to be cross-linked and cured. It only required solvent to volatilize to form a film, i.e., a physical process, which has the advantages of easy construction and stable storage. Therefore, a one-component waterborne primer was selected for substrate pretreatment in this study. Its composition and formula included a waterborne polyurethane dispersion [21] and rutile titanium dioxide [22,23]. After roller coating, the one-component water-based primer had to be placed under infrared light for curing. The specific process flow and parameters are shown in Table 2.

Table 2. Process steps for roller coating of the waterborne primer.

Product Name	Product Model	Coating Amount/g/m^2	Roll Coating Times	Remarks
Waterborne white primer	WD4500A	15	2	Double cots/IR drying

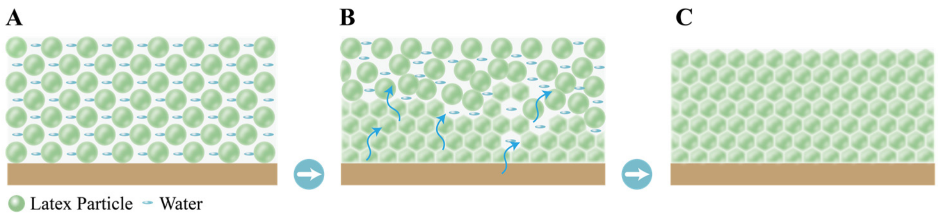

Figure 1. Schematic diagram of film-forming mechanism of single component. (**A**) Emulsion particles mixed with water solvent. (**B**) The water evaporates, and the latex particles extrude each other to form a film. (**C**) The water further evaporates and condenses to form hexagonal structures.

2.3. Waterborne Inkjet Printing Wood Grain Process

Process flow is shown in Figure 2: (1) oak plank (roll coating with water-based primer); (2) digital processing of wood grain image; (3) RIP software conversion and parameter setting; (4) placement of printing substrate; (5) printing completed.

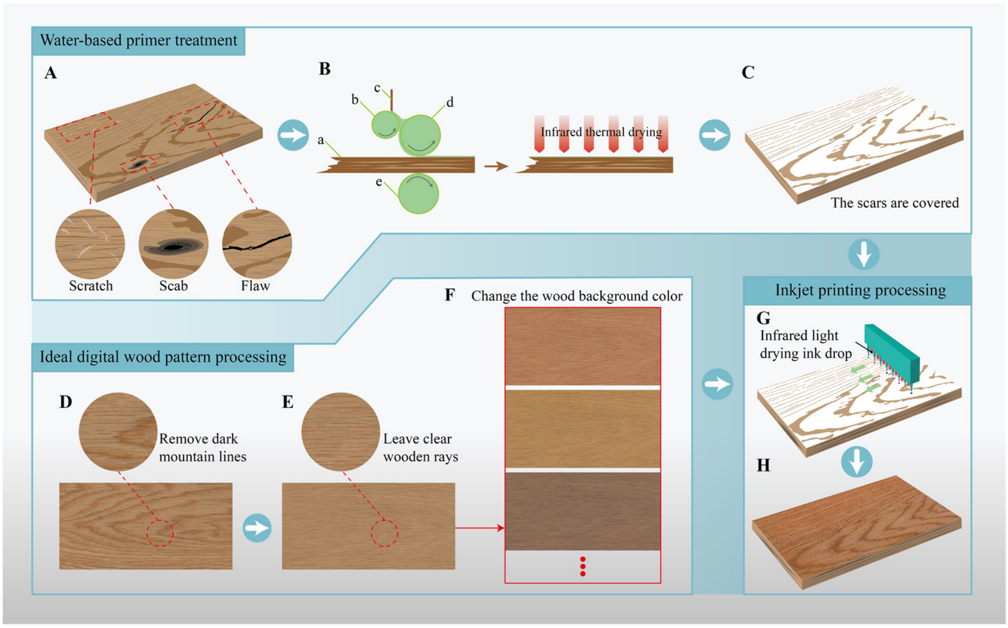

Figure 2. Waterborne inkjet printing wood grain process. (**A**) Untreated oak plank. (**B**) Process steps for roller coating and infrared curing ((**a**) Workpiece. (**b**) Dividing roller. (**c**) Scraper. (**d**) Coating roll. (**e**) Feeding roll). (**C**) The wood surface defects are covered after water-based primer roller coating. (**D**) Remove the wood grain from the tangential wood surface image. (**E**) Leave clear wooden rays. (**F**) Wood ray effect pictures with different colors. (**G**) Inkjet printing water-based coating and infrared light drying ink drops. (**H**) Wood grain simulation printing completed.

If water-based inkjet printing technology is used to print decorative wood grain surfaces, three significant factors need to be considered: the substrate surface, the image processing, and the printing method [3]. Figure 2 shows the whole process of water-based inkjet printing wood grain technology, mainly to redecorate the defective wood to improve its economic value. First of all, roll the water-based primer on the oak plank with scratches, scabs, and cracks to cover the obvious defects on the wood surface. This step will also cause the wood ray of the wood itself to be covered. Therefore, it is necessary to process the ideal wood grain underlay digitally.

There are generally three kinds of digital processing methods for wood grain images: original image scanning, digital camera capture, and computer production [24]. In this test, the original image scanning method was used to collect the natural color image of oak using a scanner. Adobe Photoshop reprocesses the image to remove surface defects such as wood grain, scabs, and stains.

The processed wood grain image was loaded into RIP software for format conversion and printing parameter setting. The precision mode was selected, with a printing speed of 6 passes and a printing precision of 1080 × 720 dpi.

The pretreatment substrate was placed on the printing table, the starting point of the printing coordinates was set, and the print image was matched to the size of the printing material.

2.4. Surface Wettability Test

The plain board and the oak plank with water-based primer roller coating were placed on the stage, respectively; five test points were randomly selected in the perpendicular direction of the tangential section, and about 1 µL of blue water-based ink was dripped into the surface test points. The process from the ink drop contacting the sample surface to diffusion during the sinking of the microprocessor was observed, and the contact angle change in the two sample surfaces was recorded.

2.5. Infrared Spectroscopy

The plain board was cut into blocks of approximately 5 mm × 5 mm × 2 mm and placed in the test chamber of the IR spectrometer. The ATR mode was used to produce an IR spectrum of this sample. The same procedure was used for the roller-coated water-based primer, and then a water-based ink was sprayed onto the oak plank to compare changes in the spectra for three main groups of wood surfaces.

2.6. SEM and EDS Analysis

The waterborne primer and inkjet oak plank were observed under an electron microscope. The sample was cut into slices measuring 5 mm × 5 mm × 2 mm and fixed on a carrier table. The slices were gold-sputtered using a vacuum blasting instrument and then placed in an electron microscope sample holder to observe the permeability of the interfacial coating and the type and content of the coating's elements on cross-sections and diameter cuts of the wood.

2.7. Measurement of Ink Dot Distribution under an Optical Microscope

The roll-coated water-based primer, water-based primer, and water-based inkjet-printed samples were sliced and placed under a microscope to observe the uniformity of the roll-coated water-based primer on the surface and the distribution characteristics of water-based inkjet ink dots from a 100× magnification perspective.

2.8. Performance Test of Waterborne Primer Coating

Adhesion, glossiness, hardness, roughness, and whiteness of paint film are the most important indicators of the performance of reactive water-based primer coatings. In this paper, the adhesion cross-cutting test was carried out according to GB/T4893.4-2013 [25], "Determination of Adhesion on Furniture Surface". Three areas were cut on the test piece, and 3M600 test tape was used to make complete contact with the paint film. The tape was smoothly removed at an angle close to 60° within 1 s, and the degree of peeling of the surface coating was comprehensively evaluated using a 0–5-point scale. The glossiness of paint film was measured using an NHG268 Gloss Meter, according to the GB4893.6-2013 method for determining the paint film's physical and chemical properties on the furniture's surface. Each group of specimens was tested five times in parallel. An 85° incidence angle gives better resolution when the 60° incidence angle gloss is lower than 10 GU, so an 85° incidence angle resolution was chosen here. According to GB/T6739-2006 [26], "Paint and Varnish Pencil Method for Determining the Hardness of Paint Film", a QHQ-type pencil scratch hardness tester was used, and three test pieces of each group were tested in parallel. We used the JB-C roughness tester and took the average value of 5 points for each test piece. We used the WSB-2 whiteness meter to test the whiteness value of the white water-based primer coating.

3. Results and Discussion

3.1. Analysis of Wood Surface Wettability

The hydrophobicity of the surface-treated plain plate and water-based primer was evaluated by measuring the ink's contact angle. As shown in Figure 3A, there were two situations after the ink dropped onto the surface of the plain plate. One is that when the ink was leveled on the smooth area, the ink drops appeared dome-shaped. With the penetration of the ink drops, the surface of the plain plate left approximately round ink spots. Second, when dropped onto concave/convex pores, the hydrophilicity and porous structure enabled water molecules to penetrate easily into the amorphous regions of the fibers [27]. The ink drops spread in two directions along the pores, forming a vertical ink line, which may seriously affect the resolution when inkjet printing on wood grain.

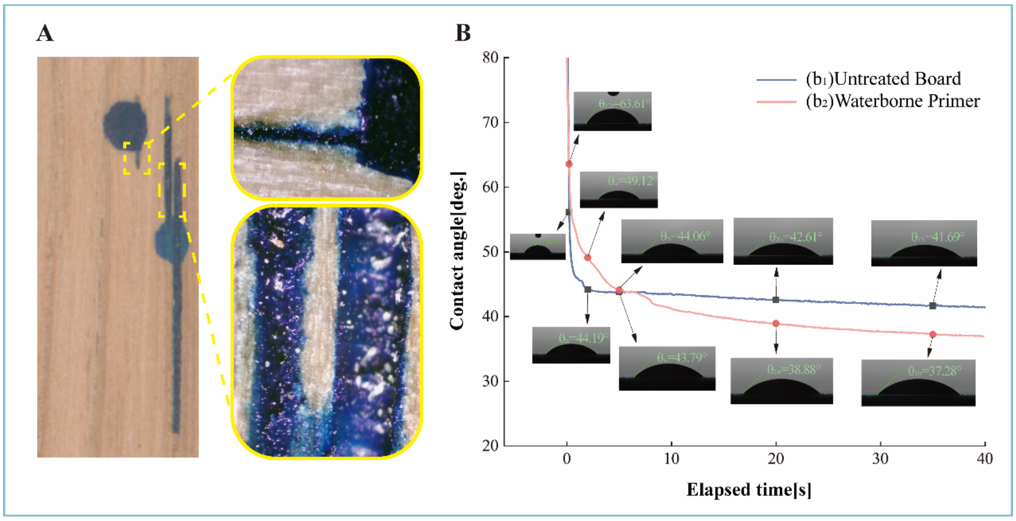

Figure 3. (**A**) Picture of ink droplet penetration in concave areas on the surface of the plain plate (×40). (**B**) Change in the surface contact angle of the plain plate ($\mathbf{b_1}$) and waterborne primer ($\mathbf{b_2}$).

The image of the ink drop contact angle on the surface of the oak plank is shown in Figure 3B. Figure 3(b_1) shows that the initial contact angle of the plain plate surface was 56.17° at 0.2 s, which rapidly changed to 44.19° at 2 s. Penetration continued to slow down after 5 s until the contact angle stabilized at 41.69°. Figure 3(b_2) shows that the initial contact angle of the surface of the oak plank coated with a water-based primer roller was 63.61° at 0.2 s, and the penetration rate continued to increase after 2 s until the contact angle reached 37.28° and gradually stabilized. The initial contact angle of the oak plank coated with a water-based primer roller was larger, and the surface penetration rate was more uniform and continuous than that of the plain board. As time passed, the contact angle of the surface of the roller-coated oak plank with water-based primer at 40 s was lower than that of the plain board. The difference was about 4.41°, indicating that the roller-coated oak plank with a water-based primer was more hydrophilic and may have better interfacial bonding performance [28].

3.2. FTIR Spectroscopy

The FTIR spectra of the oak plank after coating optimization are presented in Figure 4. Figure 4a shows untreated wood, i.e., the control group. Figure 4b is an oak plank roller-coated with a water-based primer. Figure 4c shows the water-based inkjet oak plank. New peaks appeared in the FTIR spectrum of the optimized coating, indicating that new functional groups appeared on the optimized coating's surface. The peak at 2920 cm^{-1} showed a C-H stretching vibration peak, indicating saturated CH bonds, which increased the lipophilicity of the compound. This indicates that the presence of the water-based primer can balance the water absorption of the plain board and act as an adhesive to improve the bond between the water-based ink and the plain board. The stretching vibration peak of C=O appeared at 1724 cm^{-1}, indicating the presence of carbonyl functional groups (aldehydes) [29]. The C-O stretching vibration peak appeared at 1165 cm^{-1}, indicating hydroxyl functional groups such as hydrophilic alcohols and phenols. These mainly existed in the water-based ink and may have strengthened the adhesion between the surface inkjet coating and the water-based primer.

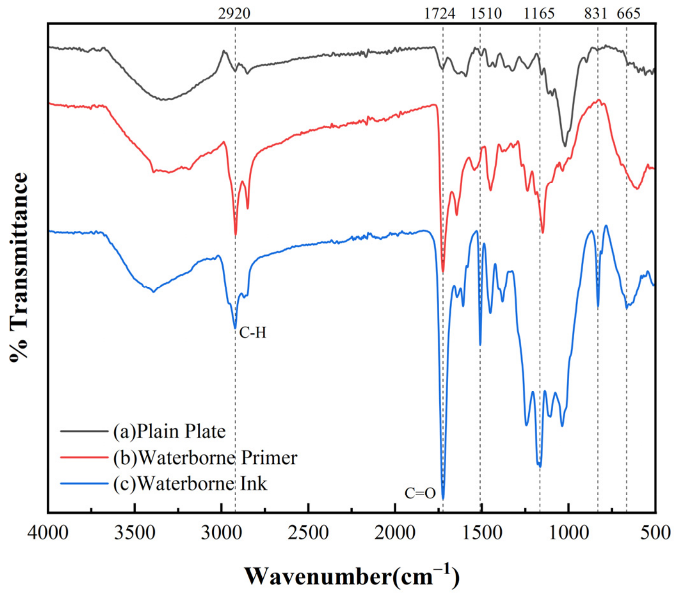

Figure 4. Infrared spectra.

3.3. SEM Morphology and EDS Element Analysis

SEM and EDS were used to study the morphology, dispersion, and elemental distribution of the waterborne primer. As shown in Figure 5, the ink penetrated the chord section of the roller-coated waterborne primer oak plank. The water-based primer formed a thin, highly absorptive layer on the surface of the wood substrate that absorbed the ink droplets. The principle of this printing technology is presented in Figure 5A. In this experiment, the roller-coated water-based primer coating can rapidly swell and absorb ink to maintain a high print quality [30]. Because the water-based primer was mainly composed of rutile titanium dioxide, it had good whiteness and coloring ability, a strong hiding power, and stable chemical properties [31]. The elemental distribution is shown in Figure 5B,C. The EDS analysis technique identifies elements based on the positions of the peaks in the spectrum. The signal intensity corresponds to the concentration of the component, and the numerous red dots in the graph show the presence of many titanium atoms, which confirms that primer penetration optimized the interfacial adhesion and color rendering.

Clear wood fibers can be seen in the chord section of the untreated plain board in Figure 5D. In contrast, a clear dividing line can be seen in Figure 5E, indicating that the top was covered with a layer of water-based primer with a depth of about 20 μm. There were no obvious penetration traces in the pores in the deeper wood fibers. Figure 5F shows an SEM image of a layer of water-based ink sprayed on the water-based primer, in which the penetration depth was about 45 μm. The water-based primer provided a high gas fastness to the dye, which swelled into the polymer. It can be estimated that the water-based primer and water-based ink coating were integrated and firmly attached to the wood surface.

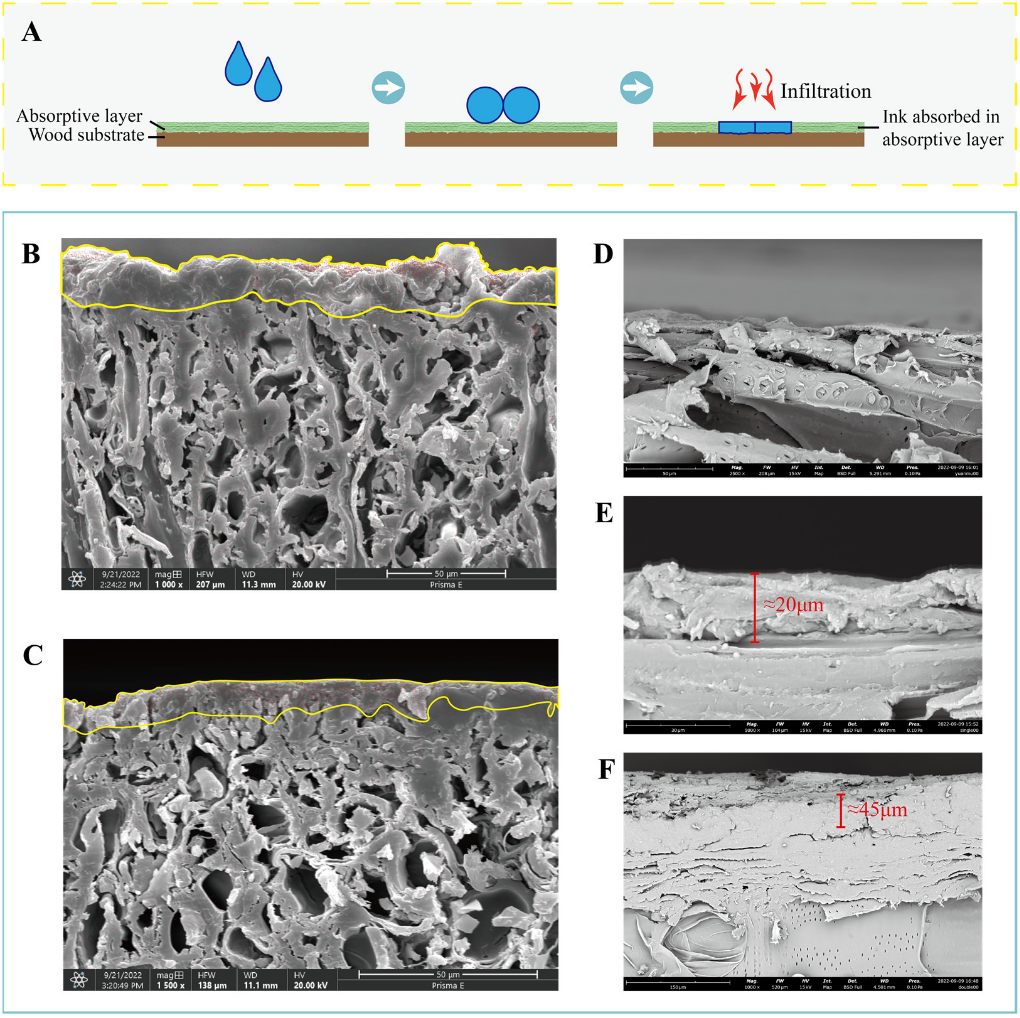

Figure 5. (**A**) Ink droplet absorption on an "inkjet" coating. (**B**,**C**) EDS spectra of the cross-section of oak multilayer board roller-coated with waterborne primer. (**D**) SEM image of the chord section of the plain plate (×2500). (**E**) SEM image of the chord section of roller-coated water-based primer (×2500). (**F**) SEM image of the chord section of water-based primer and water-based inkjet (×1000).

3.4. Microscopic Distribution Characteristics of Ink Dots

Inkjet printing quality is strongly dependent on ink–substrate interactions [32]. As shown in the microscopy image in Figure 6A,B, the oak plank with a roller-coated water-based primer could not be uniformly used at the depression due to the uneven texture of the wood surface. The blue water-based ink was evenly distributed on the surface. Even the wood grain depressions were sprayed with ink dots. This was mainly because the nozzle size of the inkjet printer was very small, and the ink droplets sprayed out were only 5 pL, allowing them to be sprayed into the gaps of the surface wood fibers to achieve a uniform dye coating. The randomness of the holes on the wood surface and the semi-closed roller coating effect of the water-based primer prevented the color coverage of the coating from achieving 100% uniformity. Therefore, the substrate coated with a water-based primer will have better color rendering of color ink, as shown in Figure 6C,D. It can be seen in Figure 6E,F that the sprayed wood still retained the natural texture and light–dark junctions. The comparison before and after water-based inkjet dyeing of the same wood shows that, while the color of the wood changed, the natural texture was maintained. The dyed wood had no excessive manual processing traces. The printed details of the digital wood grain image can be clearly seen from the enlarged detail drawing (Figure 6G,H), which can effectively use printing equipment to restore the wood ray of the wood itself.

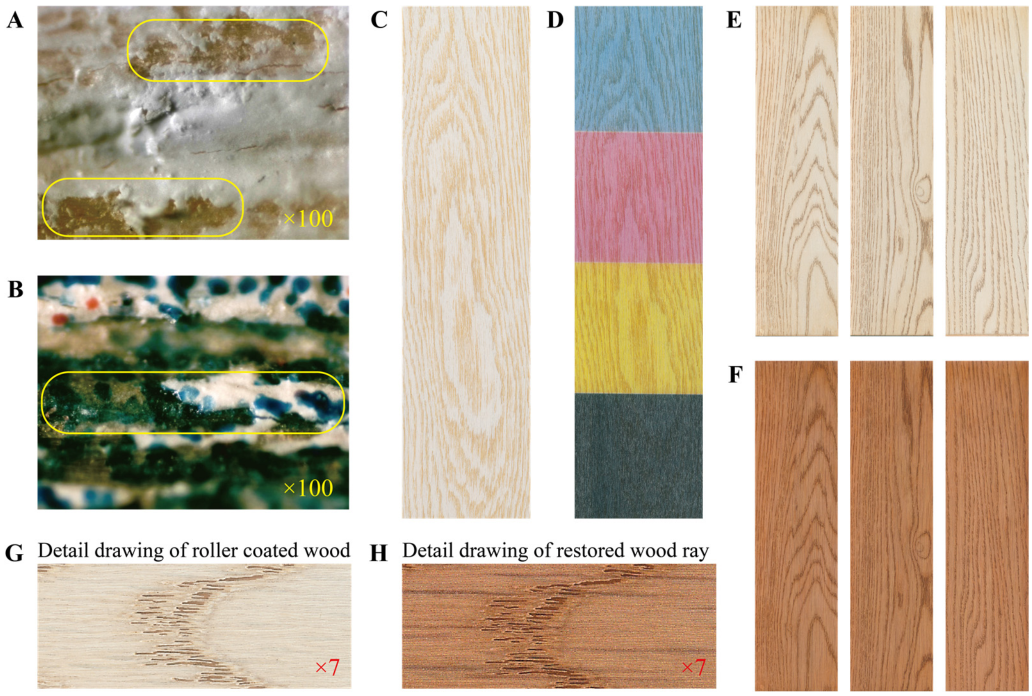

Figure 6. (**A**) Optical microscope picture of roller-coated water-based white primer (×100). (**B**) Optical microscope picture with blue water-based ink (×100). (**C**,**D**) CMYK color effect of wood roller after primer. Pictures of the wood before (**E**) and after water-based inkjet printing. (**F**,**G**) Detailed drawing of roller-coated wood (×7). (**H**) Detail drawing of restored wood ray (×7).

3.5. Performance Analysis of Water-Based Primer Film

As an adhesive layer, the water-based primer needs to adhere to the substrate firmly and carry a high-resolution inkjet print coating, which requires the paint film to have some good properties. Yan et al. investigated the self-healing and aging resistance of microencapsulated coatings on the surface of European Linden timber, using a waterborne primer process as a pretreatment of the wood to enhance the adhesion to the substrate. This prevented the coating from falling off, thus facilitating the subsequent process [14]. Their study was focused on microencapsulated coatings. In contrast, ours concentrated on the waterborne primer and explored its benefits for the following process. Table 3 shows the film characteristics of the water-based primer on the wood surface. After the water-based primer is rolled, the adhesion of the coating can reach Grade 1, and there is no peeling after the cross-cutting test. The average glossiness of five places can reach 5.6 GU. The film hardness test is at the 2H level. The average value of roughness is 2.516 µm. The whiteness value of the water-based primer is 66.6%, and all the film properties meet the national standard, meaning it can achieve the essential performance as a primer. However, this research has room for further improvement to achieve better film characteristics.

Table 3. Effect of waterborne primer on film properties.

Sample	Adhesion	Glossiness	Hardness	Roughness	Film Whiteness
water-based primer roller coating	Level 1	5.6	2H	2.516	66.6

4. Conclusions

Based on digital inkjet printing technology, this paper conducted inkjet dyeing on oak plank and studied the influence of base treatment with a one-component water-based primer on the performance of the water-based inkjet coating. On the surface coated with the one-component water-based primer, the ink droplet spreading rate was slow, the penetration time was long, and the final ink droplet contact angle was minor, so its permeability was better. The coating of the waterborne primer balanced the water absorption of the plain board. The waterborne inkjet coating contained hydrophilic groups, which could be firmly attached to the surface of the waterborne primer. The presence of many titanium atoms on the paint surface of one-component waterborne primers improves the adhesion, whiteness, and brightness of the printed paint film and has excellent hiding power. Furthermore, due to the concavity and convexity of the natural pores on the wood surface, the roller-coated water-based primer could not completely cover the wood surface. This process not only changed the color of the substrate wood surface but also retained the natural texture of the surface. This enables further inkjet color and the texture of the surface to be well unified, so the wood texture printing coating achieves a more natural effect. The interfacial properties of the substrate can also be enhanced using aqueous primer coating methods on wood with no visible wood grain. However, the decorative aspects require inkjet printing scheme adjustments, which can be further investigated in subsequent studies.

In general, this study reveals the principle of a one-component water-based primer to improve the surface of inkjet substrate wood. The process application improves the performance of the water-based inkjet coating and also represents an efficient, green method of surface decoration for wood-based panels.

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