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Novel Starch-Based Coatings to Improve the Surface, Mechanical, and Physical Performance of Recycled Paperboards for Packaging Applications

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ABSTRACT

This study developed and characterized three novel biodegradable coating formulations based on rice, wheat, and corn starches, blended with sorbitol, polyethene glycol, and carboxymethyl cellulose. These coatings were applied to recycled paperboard using a bar coater to improve its mechanical and barrier properties for packaging applications. Comprehensive evaluation revealed that the wheat starch-based coating yielded the most significant enhancements. The application of this coating increased the bursting strength of uncoated recycled paperboards by 42.42 % and edgewise compression strength (ECT) by 8.6 %, while reducing the Cobb value by 22.89 % and porosity by 10.28 %. Furthermore, it substantially improved barrier performance, reducing water vapor permeability (WVP) by 49.5 %, and enhanced optical properties, increasing brightness by 1% and reducing color difference by 4.3%. The superior color printability observed for wheat-starch-coated boards is attributed to combined improvements in surface properties and reduced porosity. Statistical validation via one-way ANOVA confirmed the significance of the results. Microscopic analysis (SEM and AFM) demonstrated improved surface evenness and smoothness for all coated samples. FTIR spectroscopy in the 960–1060 cm^{-1} region showed a decrease in light transmittance after coating, with the wheat-based formulation showing the greatest reduction (from 55 % for uncoated paperboard to 41 %), indicating effective surface coverage and interaction. The findings confirm that these starch-based coatings, particularly the wheat starch formulation, are effective in improving the strength, barrier, and printability performance of recycled paperboards. Prog Color Colorants Coat. 19 (2026), 467-483© Institute for Color Science and Technology.

1. Introduction

Today's packaging industry relies primarily on petroleum-based coating materials to improve the mechanical and barrier properties of coated paperboard [1]. In addition to their high cost, the non-biodegradability of petroleum-based products can pose significant waste disposal problems [2]. Developing eco-friendly packaging materials such as recycled paperboard and biodegradable coatings is essential for sustainable food packaging performance [3, 4]. A growing interest in eco-friendly, biodegradable polymer-based coating materials has emerged over the last decade due to increasing environmental pollution [5, 6]. Applying starch, a biodegradable material, as a coating on paperboard is gaining importance. Starch is an important material used in the paper industry due to its abundant availability and low cost [7]. From a global perspective, the paper and paperboard industry is the

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most extensive application of non-food starch [8]. Applying starch in the packaging industry primarily aims to improve surface properties. Starch is also used in pigment and functional coatings for paperboard packaging. Starch is a widely accepted raw material in packaging due to its film-forming abilities [9]. Starch is a naturally available polymer with a high molecular weight that can be depolymerised with excellent control [10]. It is water-soluble and adheres to cellulosic fibres and pigments using hydrogen bonds. The viscosity of the coating formulation influences the coating weight on paper [11]. Several researchers have reviewed various aspects of starch as a material for coating formulations and biofilm production [12]. The coated paper comprises base paper and its coating layer. The coating formulation is applied to the base paper using various methods to improve its characteristics. Coating formulations mainly comprise primary coating materials, plasticizers, and other additives to enhance coating performance. Starch and latex as coating materials on paperboard for food packaging improve their barrier properties against environmental factors at a cost-effective level [13]. The binders can be either naturally derived, such as starches and proteins, or synthetic latex, such as styrene-butadiene, poly(vinyl acetate), polyacrylate, etc. Compared to synthetic latex, starch is a cheap and naturally derived binder. However, native starch is limited by its insolubility in cold water, its propensity to retrograde, and its viscosity changes and thickening during cooking and storage [14]. The starches are modified and used in coating formulations of varying strengths to overcome these disadvantages. The addition of additives to starch adjusts the rheology and increases water retention. Increasing the starch content improves the tensile strength and modulus of elasticity of coated paperboards and reduces elongation at break [7, 15, 16]. However, excessive addition of starch in coating formulations can reduce drying speed and increase picking resistance and crack area [17]. Coating formulations containing starch and carboxymethyl cellulose (CMC) plasticised with sorbitol increase the tensile strength of the coated substrate [15]. The increase in tensile strength improves the bursting resistance of coated samples [18]. Various studies have been conducted to analyse the factors influencing the compression strength of paperboard boxes [19]. The moisture resistance of paperboard has to be improved to increase its compression strength [20]. The mechanical strength of paperboard decreases with increasing moisture content due to higher environmental humidity, which reduces the mechanical strength and lifespan of containers [21]. Paperboards coated with organic nanoparticles synthesised by imidization of styrene-maleic anhydride copolymers demonstrated good offset printability due to improved ink adhesion compared to uncoated paperboards [22]. Latex-based coating formulations form a continuous film on the paperboard, improving its smoothness [23]. The recycled paper substrate can also be used to print a wide range of colors using an offset printing press [24]. This research aims to develop and test a novel biodegradable coating formulation for recycled paperboard to enhance its suitability for food packaging applications. The objectives include improving the mechanical and barrier properties of the paperboard, ensuring its eco-friendly nature, and promoting sustainability by utilising starch-based materials. The formulation aims to provide adequate moisture resistance and mechanical strength, thereby improving the preservation and protection of food products.

2. Experimental

2.1. Materials

Four varieties of imported recycled paperboards (Twill Bright White, Twill Avorio, Prisma White, and Prisma Ivory) were obtained from Padmavati Fine Papers, Bangalore (India). These eco-friendly paperboards are selected based on their suitability for food and fast-moving consumer goods packaging applications. Rice starch, corn starch, wheat starch, sorbitol, polyethene glycol, gelatin, and carboxymethyl cellulose (CMC) were obtained from Himedia Laboratories Ltd (India). The amylose content of the rice, wheat, and corn starch was 15, 23, and 25 %, respectively.

2.2. Methods

2.2.1. Measuring the properties of recycled paper boards

The brightness (%) and colorimetric (L*, a*, b*) properties of selected uncoated paperboards were measured using Spectrophotometer D530 (Xrite, USA). The instrument was calibrated by measuring the standard white surface provided by Xrite. The brightness measurement option was selected in the paper indices tab on the spectrophotometer to measure the paperboard's brightness percentage. Colorimetric properties (L*, a*, and b*) of the paperboards were measured by selecting the color option on the instrument [25]. The optical density was measured using a densitometer (Techon GmbH DENS C301541, Germany). The densitometer was calibrated to read the surface of uncoated ITC Hi-Brite 100 GSM premium white paper (ITC, India) as the reference. Optical densities of the recycled paperboards were measured relative to the reference value. Each of these properties was measured five times (n=5), and the mean value was recorded. The recycled paperboards were categorized according to ISO 12647-2 using the standard color difference (ΔE) formula (Eq. 1) [26].

$$\Delta E = \sqrt{[\Delta L^2 + \Delta a^2 + \Delta b^2]} \tag{1}$$

where ΔE is the color difference, ΔL, Δa, and Δb are the deviation of L*, a*, and b* from the ISO standard measurements, respectively.

The bursting strength of paperboards was measured using a Bursting Strength Tester (PBD–400, Presto Instruments, India) as per TAPPI T 403. The tester was calibrated using a standard aluminium foil with a known bursting strength. The bursting strength of uncoated and coated paper boards was measured by setting the tester in board measurement mode. The ECT and RCT of samples were measured by compressing the paperboard samples on an electronic crush tester (Pack Test Crush Tester, India) as described in TAPPI T 8222. The porosity of the samples was measured using the Bendtsen method with a porosity tester (Universal Engineering Corporation, UEC–1013, USA) in accordance with ISO 5636-3. The recycled paperboard of standard size is clamped onto the tester, and a constant standard pressure difference is applied. The porosity is then measured by recording the time (s) required for air under standard pressure to pass through it. The Cobb values are measured using a Cobb sizing tester (Gurley 4180N, USA), as described in TAPPI T 441, to determine the water absorbed by the recycled paperboards in grams per square meter of the sample using a digital weighing balance. The standard-sized specimen was clamped on a Gurley-Cobb Tester, saturated with water for 60 s, and then drained. Surface water was removed by blotting with a 10 kg roller, followed by determination of the final wet weight. These properties were measured five times (n=5), and the mean values were recorded [27]. The water vapor transmission rate (WVTR) is determined by dividing the slope of the regression line of the sample weight versus time graph by the area of the film exposed to transmission (Eqs. 2 and 3).

$$WVTR = \frac{\Delta m}{\Delta t A} \tag{2}$$

$$\textit{Water vapour permeability } (WVP) = \mathrm{WVTR}\left(\frac{L}{\Delta p}\right) \tag{3}$$

where $\frac{\Delta m}{\Delta t A}$ is the moisture gain weight per time (g/s), A is the exposed surface area of the film (m^2), L is the thickness of the film (mm), and Δp is the difference in partial pressure [28].

2.2.2. Formulation and measurement of properties of coatings

Rice starch, wheat starch, and corn starch powders were used as the primary coating materials due to their ability to improve the mechanical properties of the coating. Sorbitol, polyethene glycol, gelatin, and carboxymethyl cellulose (CMC) enhance the coating's flexibility, film formability, and mechanical strength properties [29]. The solid content in the coating was maintained above 50 % (around 65 %) based on the preliminary study to achieve coating weight between 10 and 12 g/m^2 [48, 49]. 5 g of each starch (wheat/rice/corn) was separately mixed in 100 mL of distilled water to get 5 % starch solutions. Each of these 5 % starch solutions was added with 3 g of sorbitol, 2 g polyethene glycol, 0.5 g of gelatin, and 2 g of Carboxymethyl Cellulose (CMC) and stirred over a magnetic stirrer (ISKO, India) for 1 hour at 80 °C to get three uniform coating formulations [30]. Thus, the three starch-based coating formulations, namely RSF (rice starch), WSF (wheat starch), and CSF (corn starch), were obtained. The particle size, zeta potential, conductivity (Malvern Instruments Ltd., UK), viscosity (Brookfield Viscometer, UK with spindle LV04 No. 64 at 60 RPM, UK), and surface tension (Jencon Surface Tensiometer, India) of these coating formulations were measured.

2.2.3. Coating of the recycled paperboard

The coating is applied to four recycled paperboards using a K Bar Coater (RK Print Coat Instruments, UK, Number 10). The three coating formulations were applied with a standard K-bar coater at a uniform speed to a thickness of 10 µm [31]. The coat weight of all three coating formulations ranged from 10 to 12 g/m^2. As mentioned earlier, the optical, strength, and physical properties of the coated recycled paper boards were measured [32]. The image of the uncoated and coated recycled paperboards is shown in Figure 1.

2.2.4. Surface characterization of coated recycled paperboard

Atomic force microscopy (AFM; Innova SPM, Bruker, USA) images were obtained to analyse the surface roughness of uncoated and coated recycled paperboards. Surface images of uncoated and coated recycled paperboard samples were taken using a scanning electron microscope (SEM, EVO 18, Zeiss, Oberkochen, Germany) [33]. Light transmittance through uncoated and coated samples was determined using Fourier transform infrared (FTIR) analysis (Shimadzu Corporation, Japan).

2.2.5. Printing on the recycled paperboard and measurement of colorimetric properties

Uncoated and coated paperboards were printed using IGT C1 offset Printability Tester (IGT Testing Systems, Netherlands) using DIC offset black ink (DIC, India) [34]. The printing was carried out on uncoated and coated paperboards at a constant printing speed of 0.3 m/s using a printing pressure of 400 N. L* a* b* and ΔE values of black, cyan, magenta, and the yellow printed patches on coated recycled paperboards were measured using a Spectrophotometer 530 (X-Rite, USA) [35].

2.2.6. Measurement of box compression strength (BCT)

2D design of a full-seal end-style carton (5 × 5 × 5 inches) is created using ESKO Graphics Artios CAD 12 software (ESKO, Singapore), as shown in Figure 2, and converted to a box using a cutting plotter (VH–60, SKYCUT, China) after viewing it in 3D mode. The cartons were glued on top and bottom using Fevicol (Pidilite Industries Ltd, India) adhesive. The box compression strength is measured using a Mini Carton compression tester (Pack Test, India) as described in the TAPPI standard. The Pack Test Edge Compression tester was weight-calibrated using a 20 Kg weight, and then set to Destruction Mode in the settings tab of the tester using the control panel. The boxes were then crushed to measure the ECT value. The average value of the five measurements was recorded.

Figure 1: Image of uncoated (a) and coated recycled paper boards with RSF (b), WSF (c) and CSF (d) formulations.

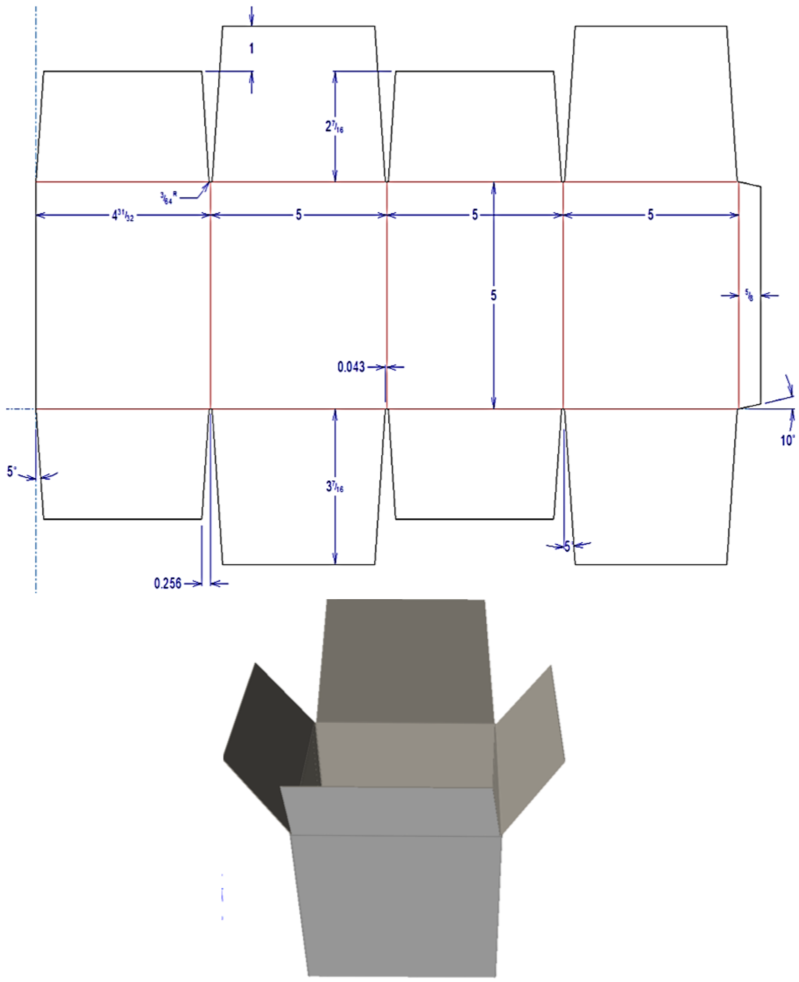

Figure 2: 2D and 3D design of carton (linear dimensions are in inches).

2.2.7. Statistical analysis using analysis of variance (ANOVA)

The influence of three different starch-based coating formulations on strength and physical properties, and box compression strength (BCT), was analysed using one-way ANOVA in Python [36]. A one-way ANOVA was used to determine whether the means of the properties of four selected uncoated recycled paperboard types differ significantly after coating with three coating formulations [18].

3. Results and Discussion

3.1. Categorization of recycled paperboard

The L*, a*, b*, and brightness of ISO 12647-2 standard paper types are shown in Table 1. The colorimetric values and ISO classification of selected recycled paperboards are presented in Table 2

3.2. Properties of coating formulations

The measured properties of RSF, WSF, and CSF coating formulations are given in Table 3.

Table 1: L*, a*, b* and brightness of ISO 12647-2 paper type.

Paper type (ISO type)	L*	a*	b*	Brightness (%)
Gloss-coated, wood-free (1)	93	0	-3	89
Matte-coated, wood-free (2)	92	0	-3	89
Gloss-coated, web (3)	87	-1	3	70
Uncoated, white (4)	92	0	-3	93
Uncoated, slightly yellowish (5)	88	0	6	73

Table 2: Classification of selected recycled paper boards into ISO paper type (n = 5).

Recycled paper boards	L*	a*	b*	Brightness (%)	ISO type
Twill Bright White (I)	86.06 ± 1.84	5.92 ± 0.24	5.37 ± 0.15	72.2 ± 1.03	5
Twill Avorio (II)	84.38 ± 1.58	1.86 ± 0.18	0.53 ± 0.04	90.2 ± 1.82	4
Prisma White (III)	88.22 ± 1.75	7.14 ± 0.21	6.34 ± 0.18	71.3 ± 1.05	5
Prisma Ivory (IV)	94.458 ± 1.86	6.51 ± 0.19	7.88 ± 0.21	71.1 ± 1.04	4

Table 3: Properties of three coating formulations (n = 5).

Coating	Viscosity (CP at 60 RPM)	Surface tension (Dynes/ cm)	Particle size (nm)			Zeta Potential (mV)
			Highest	Lowest	Mean	
RSF	1152 ± 12	43.86 ± 20	135.7 ± 50	123.3 ± 20	135.2 ± 40	-25.7 ± 1.50
WSF	1181 ± 15	44.6 5± 20	136.2 ± 40	124.7 ± 30	130.5 ± 50	-24.6 ± 1.50
CSF	1226 ± 17	45.40 ± 30	131.7 ± 30	125.6 ± 30	134.3 ± 50	-26.7 ± 20

The viscosity of the coating formulation in the higher range can provide uniform coating and a smoother coated surface [11]. The highest and lowest particle sizes for each coating formulation displayed by the instrument indicate the largest and smallest particles in the coating solution, which will determine the particle size distribution on the coated surface of recycled paperboards. The mean particle size is the average particle size across all particles displayed on the instrument for each coating formulation. The particle size in the CSF coating formulation is smaller than in RSF and WSF formulations. Uniform particle size in CSF results in a narrow particle distribution and an open structure on the coated surface. The larger differences in the particles of coating formulation WSF leads to the closely packed network structure on the surface of coated recycled paperboard. This arrangement will reduce porosity and improve the strength and barrier performance of the coated samples [37]. The Zeta potential of all three coating formulations is close to –30 mV, indicating better coating stability. Stable coating provides a uniformly coated surface [38].

3.3. Colorimetric, strength, and physical properties of coated recycled paperboards

Recycled paperboards were coated with formulations RSF, WSF, and CSF for 10 µm thickness. The brightness, ΔE, and optical density values for uncoated and coated samples are presented in Tables 4, 5, and 6, respectively.

Tables 4 and 5 clearly show that the brightness and ΔE values of uncoated and recycled paperboard samples coated with formulations RSF, WSF, and CSF are close to the ISO values (Table 1). From Table 6, it can be observed that the differences in optical density between uncoated and coated recycled paperboards are negligible. The RSF, WSF, and CSF formulations likely yielded an effective particle size distribution and a binder-to-pigment ratio, facilitating the formation of a coherent film that covers the primary, often rougher and more porous, recycled fibres. Bursting strength (Kg/cm^2), Cobb (g/m^2), porosity (s), and ECT (N) are presented in Tables 7, 8, 9, and 10.

Table 4: Brightness of uncoated and coated recycled boards (n = 5).

Paperboard type	Brightness (%) of paperboard			
	Uncoated	Coated		
		RSF	WSF	CSF
Twill Bright White	87.25 ± 2.34	86.55 ± 2.15	88.56 ± 1.42	88.32 ± 2.65
Twill Avorio	69.62 ± 1.23	70.16 ± 1.45	71.45 ± 1.62	73.43 ± 2.27
Prisma White	88.45 ± 2.14	88.56 ± 1.42	85.43 ± 1.23	91.87 ± 2.38
Prisma Ivory	72.45 ± 1.23	74.56 ± 1.42	75.56 ± 1.05	75.85 ± 2.16

Table 5: ΔE values for uncoated and coated recycled boards (n = 5).

Paperboard type	Color difference (ΔE) of paperboard			
	Uncoated	Coated		
		RSF	WSF	CSF
Twill Bright White	4.3 ± 0.25	5.2 ± 0.21	4.6 ± 0.24	5.0 ± 0.14
Twill Avorio	3.7 ± 0.18	4.54 ± 0.19	3.9 ± 0.18	4.38 ± 0.23
Prisma White	5.21 ± 0.20	5.2 ± 0.21	4.8 ± 0.14	5.55 ± 0.15
Prisma Ivory	5.75 ± 0.30	6.1 ± 0.25	4.85 ± 0.22	5.84 ± 0.23

Table 6: Optical density values for uncoated and coated recycled boards (n = 5).

Paperboard type	Optical Density of paperboard			
	Uncoated	Coated		
		RSF	WSF	CSF
Twill Bright White	0.07 ± 0.01	0.09 ± 0.01	0.11 ± 0.01	0.12 ± 0.01
Twill Avorio	0.05 ± 0.01	0.06 ± 0.01	0.07 ± 0.01	0.08 ± 0.01
Prisma White	0.08 ± 0.01	0.14 ± 0.01	0.11 ± 0.01	0.14 ± 0.01
Prisma Ivory	0.03 ± 0.01	0.05 ± 0.01	0.06 ± 0.01	0.07 ± 0.01

Table 7: Bursting strength for uncoated and coated recycled paperboards (n = 5).

Paperboard type	Bursting strength (kg/cm^2) of paperboard			
	Uncoated	Coated		
		RSF	WSF	CSF
Twill Bright White	4 ± 0.12	4 ± 0.15	5 ± 0.14	5.5 ± 0.18
Twill Avorio	4 ± 0.15	4 ± 0.12	6 ± 0.16	5 ± 0.16
Prisma White	4 ± 0.13	4 ± 0.21	6.5 ± 0.2	5 ± 0.2
Prisma Ivory	4.5 ± 0.18	4.5 ± 0.22	6 ± 0.18	5 ± 0.15

Table 8: Cobb values for uncoated and coated recycled paperboards (n = 5).

Paperboard type	Cobb (g/m^2) of paperboard			
	Uncoated	Coated		
		RSF	WSF	CSF
Twill Bright White	33.68 ± 1.15	29 ± 1.18	24.5 ± 1.05	26.4 ± 1.04
Twill Avorio	28.81 ± 1.07	29.5 ± 1.45	24.7 ± 1.15	26.6 ± 1.15
Prisma White	30.34 ± 1.07	29 ± 1.12	24.9 ± 1.30	26. 2 ± 1.4
Prisma Ivory	28.71 ± 1.44	30 ± 1.10	24.8 ± 1.15	26.4 ± 1.18

Table 9: Porosity of uncoated and coated recycled paperboards (n = 5).

Paperboard type	Porosity (s) of paperboard			
	Uncoated	Coated		
		RSF	WSF	CSF
Twill Bright White	300 ± 4.38	318 ± 3.83	329 ± 3.54	321 ± 3.84
Twill Avorio	282 ± 3.54	298 ± 3.43	315 ± 3.86	307 ± 3.74
Prisma White	318 ± 5.42	334 ± 4.54	356 ± 4.56	335 ± 4.75
Prisma Ivory	295 ± 4.98	312 ± 3.85	332 ± 4.65	315 ± 3.85

Table 10: ECT of uncoated and coated recycled paperboards (n = 5).

Paperboard type	ECT (N) of paperboard			
	Uncoated	Coated		
		RSF	WSF	CSF
Twill Bright White (I)	300 ± 4.54	309 ± 3.54	322 ± 3.65	317 ± 2.96
Twill Avorio (II)	295 ± 4.35	314 ± 3.86	324 ± 3.86	320 ± 3.53
Prisma White (III)	280 ± 3.54	302 ± 3.86	307 ± 3.44	306 ± 2.85
Prisma Ivory (IV)	300 ± 3.65	316 ± 4.38	323 ± 3.87	318 ± 2.94

It is observed from Tables 7 to 10 that the bursting strength and ECT of recycled boards increased, while their porosity and Cobb decreased after coating. These improvements are primarily attributed to the development of a continuous, compact coating layer that effectively seals surface pores and reinforces fibre–fibre interactions, a phenomenon extensively documented for polysaccharide-based coatings on paper substrates [9]. Sorbitol, incorporated as a plasticizer in starch-based coating formulations (derived from rice, wheat, and corn), plays a pivotal role in tailoring intermolecular interactions. By reducing the stretching of O–H bonds within starch molecules, sorbitol facilitates the formation of a robust hydrogen-bonding network among starch, water, and other coating components, such as carboxymethyl cellulose (CMC) and polyethene glycol (PEG). This strengthened network enhances coating cohesion and adhesion to the paperboard surface, ultimately improving mechanical performance [39]. The relatively high crystallinity of CMC present in all three formulations contributes significantly to the enhanced surface strength and stiffness of the coated recycled boards. The ordered arrangement of CMC chains promotes efficient stress transfer across the coating layer, thereby improving key mechanical properties such as bursting strength and edge crush resistance (ECT), consistent with previous findings on cellulose derivative coatings [15].

Among the three formulations, recycled paperboards coated with the wheat starch-based formulation (WSF) demonstrated superior performance, exhibiting higher bursting strength and edge crush resistance (ECT), along with reduced porosity and lower Cobb values compared to rice starch–based (RSF) and corn starch–based (CSF) coatings. Compared with uncoated recycled paperboard, the wheat starch coating increased the bursting strength and edgewise compression strength (ECT) by 42.42 % and 8.6 %, respectively. These mechanical improvements are attributed to the formation of a dense, well-adhered coating layer that reinforces inter-fibre bonding and improves stress transfer under compressive loading. Concurrently, the coating significantly reduced moisture-related properties, as evidenced by a 22.89 % decrease in Cobb value and a 10.28 % reduction in porosity, indicating effective pore sealing and diminished capillary water uptake. These improvements are primarily attributed to the greater crystallinity of wheat starch, which promotes tighter molecular packing and stronger intermolecular bonding within the coating matrix. Such increased crystallinity not only enhances mechanical strength but also minimizes water penetration pathways, thereby improving barrier properties [38]. CMC, polyethene glycol, and starch have resulted in a higher degree of crosslinking and polymer chain enlargement, resulting in denser and mechanically stronger coating structures. This has increased the mechanical strength (bursting strength and ECT) and decreased the physical properties (porosity and Cobb) of recycled paperboards when coated with three types of starch-based coating formulations. The reduced porosity of coated recycled paperboards results in lower water absorption and a longer useful lifespan. The higher flexibility imparted by CMC enhances coating uniformity, mitigates microcrack formation, and ensures better stress distribution under compressive and bursting loads. Wheat starch, when plasticized with sorbitol, forms a coating layer with superior tensile strength compared to rice- and corn-starch systems, owing to its higher amylose content and crystalline fraction. On the other hand, rice- and corn-starch coatings also exhibit higher onset and peak thermal degradation temperatures, indicating greater thermal stability relative to wheat-starch-coated films, a behaviour linked to variations in granular structure and amylopectin branching density. Rice starch plasticised with sorbitol and PEG forms extensive hydrogen-bonding interactions that improve film flexibility and resistance to mechanical stresses encountered during high-speed paperboard processing [37]. Reported crystallinity values for native starch powders of wheat (≈49 %), corn (≈40 %), and rice (≈39 %) further elucidate the observed differences in mechanical and barrier performance among the coated samples. Additionally, sorbitol enhances chain mobility within the starch matrix, facilitating molecular rearrangement and crystallite growth during film formation, thereby increasing the overall crystallinity of the coating layer [37].

It can be seen from Table 11 that the WVP of the uncoated recycled paperboards used in the study ranges from 0.0023 to 0.0028 g.mm/ (m². day.mmHg). The WVP of the coated recycled boards ranges from 0.0011 to 0.0020 g.mm/(m². day.mmHg). Comparing these results, it's evident that coated recycled paperboards have shown significantly lower WVP when compared to uncoated recycled paperboards [14]. The recycled paperboards with WSF have shown the least WVP compared to those coated with RSF and CSF formulations. Twill Avorio recycled paperboard coated with WSF formulation exhibits the lowest WVP, followed by Twill Bright White, Prisma White, and Prisma Ivory.

3.4. Printability properties of coated recycled paperboards

ΔE values of black, cyan, magenta, and yellow printed images on uncoated and coated recycled paperboards were calculated using equation (i) are reported in Tables 12 to 15 [4].

It can be seen from Tables 12 to 15 that the color difference of the black, cyan, magenta, and yellow, printed on recycled paperboards decreases after coating. Comparing these results, it's evident that recycled paperboards coated with WSF formulation have shown significantly lower ΔE followed by recycled paperboards coated with formulations CSF and RSF formulations [9].

Table 11: WVP for uncoated and coated recycled paperboards (n = 5).

Paperboard type	WVP (g.mm/ (m^2.day.mmHg)) of paperboard			
	Uncoated	Coated		
		RSF	WSF	CSF
Twill Bright White (I)	0.0025	0.0019	0.0012	0.0015
Twill Avorio (II)	0.0023	0.0018	0.0011	0.0014
Prisma White (III)	0.0027	0.0019	0.0014	0.0017
Prisma Ivory (IV)	0.0028	0.0020	0.0015	0.0018

Table 12: ΔE values for uncoated and coated recycled boards for black ink (n = 5).

Paperboard type	Color difference (ΔE) of paperboard			
	Uncoated	Coated		
		RSF	WSF	CSF
Twill Bright White (I)	7.0 ± 0.20	6.0 ± 0.20	4.5 ± 0.25	5.4 ± 0.15
Twill Avorio (II)	7.5 ± 0.15	6.4 ± 0.20	4.8 ± 0.20	5.6 ± 0.25
Prisma White (III)	7.5 ± 0.20	5.5 ± 0.25	4.6 ± 0.20	5.8 ± 0.20
Prisma Ivory (IV)	7.8 ± 0.20	5.6 ± 0.25	4.8 ± 0.25	6.0 ± 0.25

Table 13: ΔE values for uncoated and coated recycled boards for cyan ink (n = 5).

Paperboard type	Color difference (ΔE) of paperboard			
	Uncoated	Coated		
		RSF	WSF	CSF
Twill Bright White (I)	3.5 ± 0.20	4.5 ± 0.20	1.5 ± 0.25	2.5 ± 0.15
Twill Avorio (II)	3.6 ± 0.15	4.8 ± 0.20	1.8 ± 0.20	2.6 ± 0.25
Prisma White (III)	3.5 ± 0.20	4.2 ± 0.25	1.6 ± 0.20	2.8 ± 0.20
Prisma Ivory (IV)	3.2 ± 0.20	4.4 ± 0.25	1.7 ± 0.25	2.4 ± 0.25

Table 14: ΔE values for uncoated and coated recycled boards for magenta ink (n = 5).

Paperboard type	Color difference (ΔE) of paperboard			
	Uncoated	Coated		
		RSF	WSF	CSF
Twill Bright White (I)	7.5 ± 0.15	6.5 ± 0.15	4.8 ± 0.20	5.5 ± 0.20
Twill Avorio (II)	7.8 ± 0.20	6.6 ± 0.15	4.6 ± 0.15	5.4 ± 0.20
Prisma White (III)	7.6 ± 0.15	6.8 ± 0.25	4.5 ± 0.15	5.2 ± 0.15
Prisma Ivory (IV)	7.2 ± 0.15	6.4 ± 0.20	4.7 ± 0.20	5.6 ± 0.20

Table 15: ΔE values for uncoated and coated recycled boards for yellow ink (n = 5)

Paperboard type	Color difference (ΔE) of paperboard			
	Uncoated	Coated		
		RSF	WSF	CSF
Twill Bright White (I)	6.6 ± 0.20	5.8 ± 0.20	3.5 ± 0.25	4.4 ± 0.15
Twill Avorio (II)	6.8 ± 0.15	5.5 ± 0.20	3.4 ± 0.20	4.6 ± 0.25
Prisma White (III)	6.4 ± 0.20	5.4 ± 0.25	3.6 ± 0.20	4.8 ± 0.20
Prisma Ivory (IV)	6/2 ± 0.20	5.6 ± 0.25	3.5 ± 0.25	4.6 ± 0.25

3.5. Statistical analysis

The improvements in the physical properties of recycled paperboards after their coating have been analyzed by testing the hypothesis at a 5 % significance level. The following hypothesis is tested using the one-way ANOVA method using Python programming language (Google Colab, Google) [40, 41].

Ha: A significant difference exists in the bursting strength, Cobb, porosity, ECT, and WVP of recycled paper boards after coating using formulations RSF, WSF, and CSF.

Ho: There is no significant difference in the bursting strength, Cobb, porosity, ECT, and WVP of recycled paperboards after coating using formulations RSF, WSF, and CSF.

The results of ANOVA using Python programming language (Google Colab, Google) to evaluate the statistical significance of coating the recycled paper-boards with formulations RSF, WSF, and CSF are presented in Table 16. The Python programming codes are given in supplementary material (Figure s1 to Figure s3).

The results of ANOVA (Table 16) indicate that the calculated p-values are lower than 0.05. Hence, it can be concluded that the influence of coating on the bursting strength, Cobb, porosity, ECT, and WVP of recycled paperboards are significant after coating with formulations RSF, WSF, and CSF at a 5 % significance level [42, 43].

A post-hoc Tukey’s HSD test was performed to identify which specific pairwise comparisons between the measured properties of recycled paperboards are responsible for the overall significant difference observed in ANOVA results [44]. Bursting strength, Cobb, porosity, and ECT were substantial between uncoated and coated recycled paperboards for all the formulations. The bursting strength, Cobb, porosity, and ECT between recycled paperboards coated with formulations WSF and RSF were found to be significant. Still, they remained insignificant compared to those coated with CSF formulations.

3.6. Microstructural analysis

3.6.1. Atomic force microscopy (AFM) analysis

AFM analysis is performed to investigate the surface roughness of four types of recycled paperboards coated with RSF, WSF, and CSF for a coating thickness of 10 μm Figure 3 a-d shows the AFM images of uncoated and coated Prisma white recycled paperboard. Its surface roughness influences the strength and physical properties of paperboard. Ra (average surface roughness) and Rq (root mean square roughness) of uncoated and coated (RSF, WSF, and CSF) recycled paperboards are listed in Table 17.

Table 16: F and p values for the properties of uncoated and coated paperboards.

Properties	Statistical analysis (one-way ANOVA) result		
	F	p	Conclusion
Bursting strength	19.85	0	Significant
Cobb	19.34	0	Significant
Porosity	3.64	0	Significant
ECT	11.49	0	Significant
WVP	38.87	0	Significant

Table 17: Comparison of Rq and Ra values for three coating formulations.

Paperboard type	Surface roughness (nm) of paperboard							
	Uncoated		Coated					
			RSF		WSF		CSF	
	Rq (nm)	Ra (nm)	Rq (nm)	Ra (nm)	Rq (nm)	Ra (nm)	Rq (nm)	Ra (nm)
Twill Bright White (I)	174	145	165	138	133	110	145	126
Twill Avorio (II)	176	149	170	142	140	111	151	124
Prisma White (III)	176	145	168	136	140	108	153	127
Prisma Ivory (IV)	177	145	169	137	145	114	158	123

It is evident from Table 17 and Figure 3 that surface roughness (Rq and Ra) values of Prisma white recycled paperboard are minimal when coated with WSF formulation. Hence, we can infer that the recycled paperboard coated with formulation WSF has a smoother surface (Figure 3c) when compared to those with RSF (Figure 3b) and CSF (Figure 3d) formulations [42-44].

3.6.2. Scanning Electron Microscopy (SEM) analysis

Scanning electron microscopy (SEM) images of uncoated and coated Prisma white recycled paperboard are shown in Figure 4. The surface of uncoated recycled paperboard is seen as highly porous and uneven (Figure 4a).

The coating of recycled paperboard has sealed the valleys on its surface. However, it is observed that the recycled paper board coated with coating formulation WSF (Figure 4c) showed much-reduced pores and surface unevenness compared to those coated with formulations RSF (Figure 4b) and CSF and (Figure 4d). This result is in line with that obtained by AFM analysis.

3.6.3. Fourier-transform infrared (FTIR) analysis

FTIR analysis is used for analyzing the interaction between starch molecules and plasticizers. The light transmittance (% T) of uncoated and coated Prisma white recycled paperboard measured using FTIR absorption spectroscopy is shown in Figure 5. The light transmittance of coated Prisma white recycled paperboard has reduced after coating with all three starch-based formulations (rice/ wheat/ corn). Recycled paper board coated with formulation WSF has shown the least transmittance compared to other formulations.

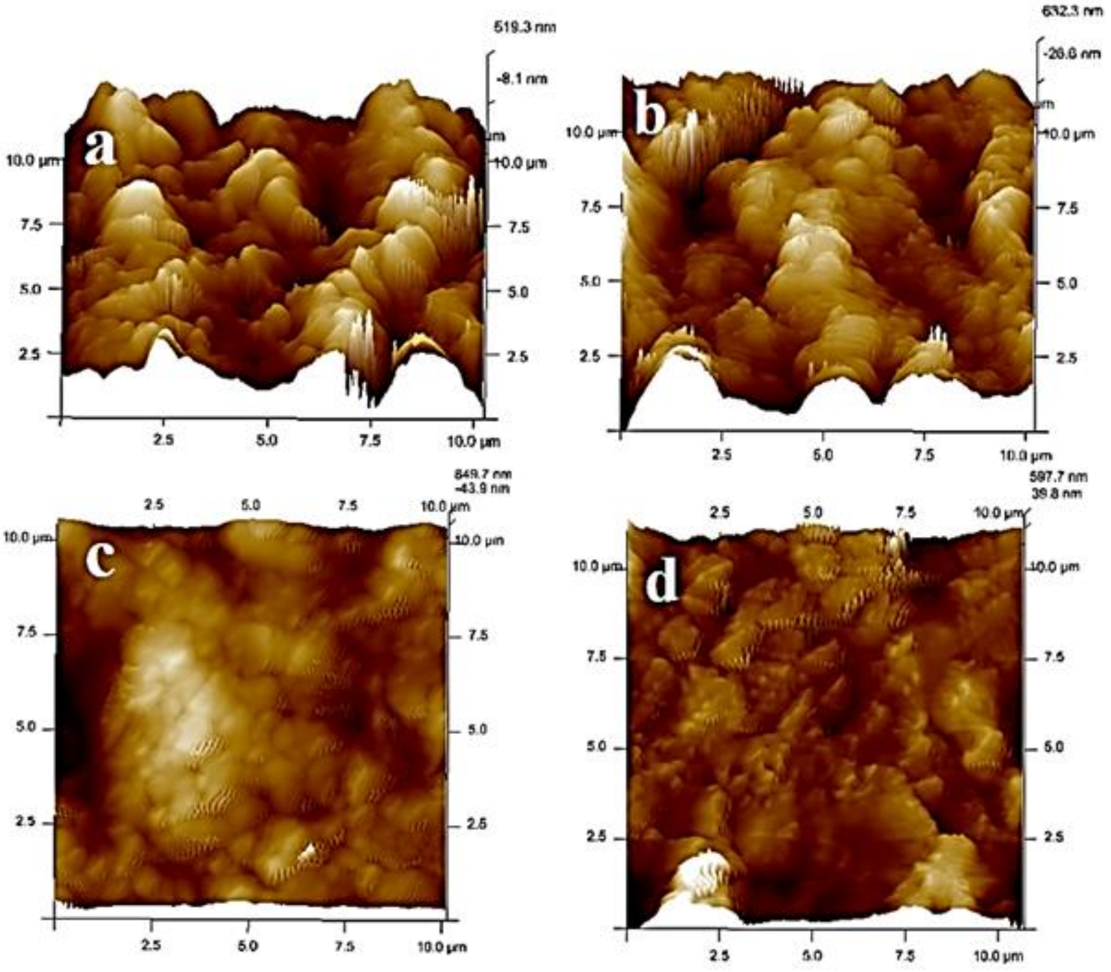

Figure 3: AFM images of uncoated (a) and coated Prisma white recycled paper board with RSF (b), WSF (c) and CSF (d) formulation.

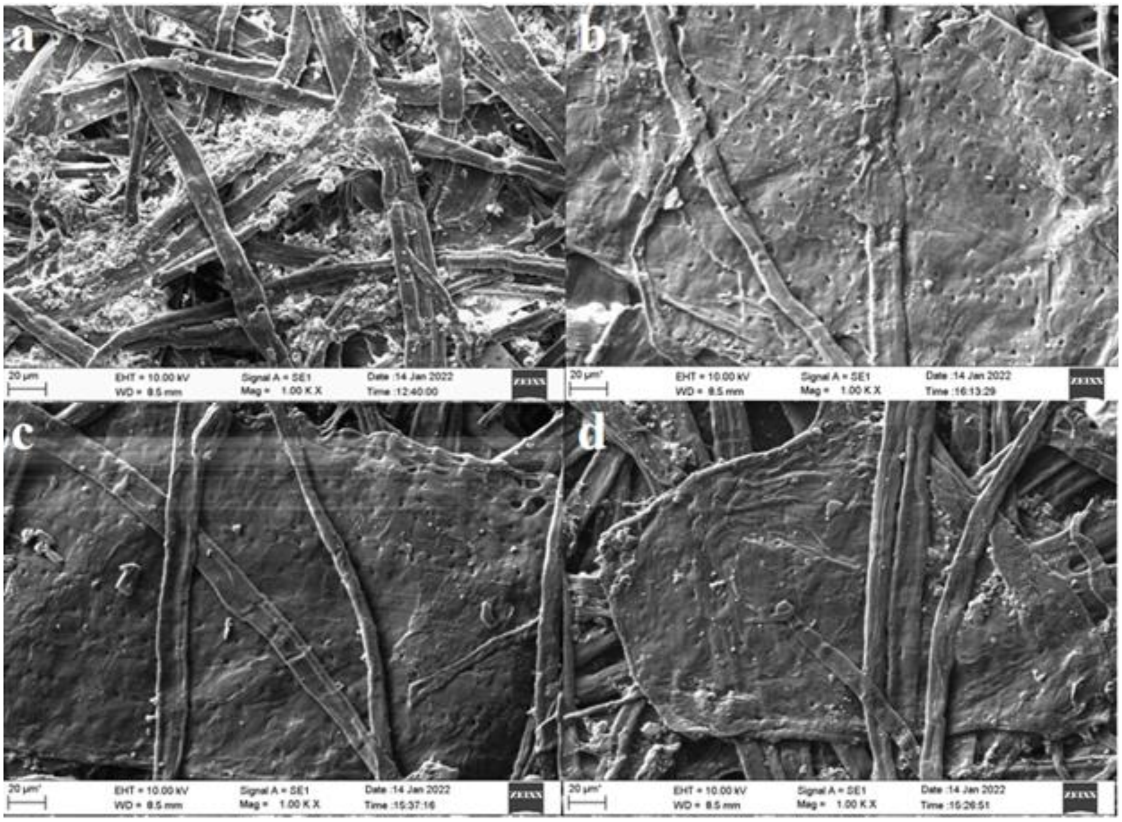

Figure 4: SEM images of Prisma whiteboard (a) uncoated, (b) coated with RSF, (c) coated with WSF, and (d) coated with formulation CSF.

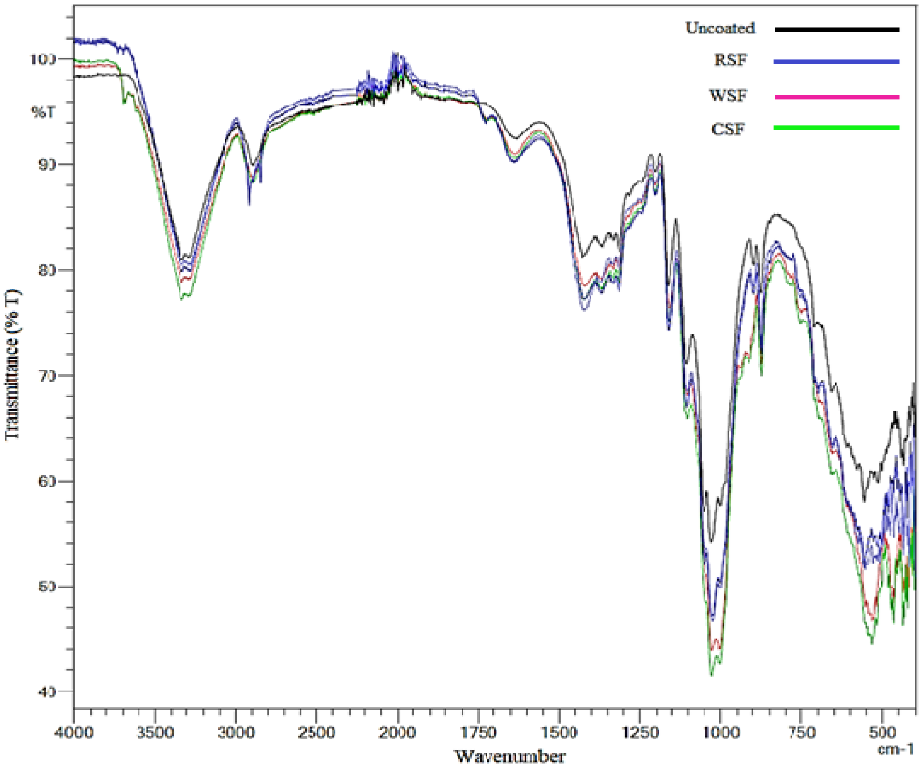

Figure 5: FTIR spectra of uncoated and coated Prisma white paperboard.

Table 18: BCT of boxes before and after coating (n = 5).

Paper board type	BCT (kgf)			
	Uncoated	Coated		
		RSF	WSF	CSF
Twill Bright White (I)	4 ± 0.05	5 ± 0.1	5 ± 0.08	4.4 ± 0.06
Twill Avorio (II)	4 ± 0.07	4.5 ± 0.06	5.3 ± 0.06	4.5 ± 0.05
Prisma White (III)	4.5 ± 0.08	4.8 ± 0.08	4.8 ± 0.05	4.5 ± 0.07
Prisma Ivory (IV)	4.4 ± 0.1	4.5 ± 0.05	4.8 ± 0.07	4 ± 0.04

The light transmittance at 960-1060 cm^{-1} wavenumber region for recycled paperboard coated with WSF formulation is the lowest (41 %), followed by those coated with CSF formulation (44 %) and RSF formulation (48 %). Uncoated recycled paperboard has shown higher light transmittance (55 %) in 960-1060 cm^{-1} wavenumber region. The lowest light transmittance of WSF coating formulation is mainly due to wheat starch's higher degree of crystallinity compared to those with corn and rice starches [45]. The increased crystallinity of coated film enhances the resistance to light transmittance. The recycled paperboards coated with rice starch-based formulation have shown the highest light transmittance. The lower surface pores and closely packed structure of recycled paperboard coated with formulation WSF block more light than recycled paperboard coated with RSF and CSF-based coating formulations [46]. The relatively larger surface pores of the RSF coating might have led to greater light transmittance (Figure 5) [47, 48, 49].

3.7. Box compression strength (BCT)

The values of box compression strength (BCT) of boxes made from uncoated and coated recycled paper boards with formulations RSF, WSF, and CSF are given in Table 18.

It can be observed from Table 18 that the BCT of boxes made from recycled paperboard was increased after their coating. The recycled paperboards coated with formulation WSF have shown higher BCT than those coated with RSF and CSF. The p-value (0.045) computed using one-way ANOVA (Table 16) is less than 0.05 [43, 44]. Hence, the differences in the BCT of boxes (Table 18) made from uncoated and coated recycled paperboards with formulations RSF, WSF, and CSF are significant.

4. Conclusions

The three eco-friendly coating formulations, RSF, WSF, and CSF, were prepared and applied to four types of recycled boards using a K Bar Coater to a thickness of 10 µm. The brightness, ΔE, bursting strength, Cobb, porosity, and ECT of coated recycled board samples were measured and compared with those of uncoated recycled board samples. The recycled paperboards coated with WSF significantly enhanced their functional performance. The coating conferred superior barrier properties, achieving a 49.5 % reduction in water vapor permeability and a 10.3 % decrease in porosity. Mechanical strength was notably improved, with bursting strength increasing by 42.4 % and edgewise compression strength by 8.6 %. Additionally, water resistance was considerably enhanced, as evidenced by a 22.9 % reduction in the Cobb value. Optical characteristics and printability have also improved due to reduced colour variation and the maintenance of the brightness of the coated surface at par with ISO values. The coated recycled paperboards' lower water vapor permeability values (0.0011–0.0020 g.mm/(m^2.day.mmHg)) suggest their suitability for packaging fast-moving consumer goods. The results were statistically validated by testing the hypothesis using ANOVA and Python. The higher crystallinity of CMC and starch molecules, along with the flexibility of the coated layer, has improved the mechanical strength properties of recycled paperboards after coating. The higher crystallinity of wheat starch and CMC has increased the mechanical strength of coated recycled paperboards. CMC, polyethene glycol, and rice starch in the coating formulation have increased crosslinking, improving mechanical strength. AFM and SEM analysis revealed a smoother surface and significantly reduced surface pores when the recycled paperboard was coated with the WSF formulation. FTIR analysis in this paper showed the lowest light transmittance for paperboard coated with WSF formulation. The recycled paperboard with WSF formulation showed higher box compression strength than those coated with RSF and CSF formulations.

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5. References

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