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The Influence of PLA and CMC Coatings on Mechanical and Physical Properties of Recycled Packaging Papers

Utjecaj PLA i CMC premaza na mehanička i fizička svojstva recikliranoga ambalažnog papira

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ABSTRACT • *In this study, the effect of polylactic acid (PLA) and carboxymethyl cellulose (CMC) coatings on the mechanical and physical properties of recycled packaging papers was investigated. Paper samples were produced according to the TAPPI T205-SP-02 standard using waste office paper and old corrugated cardboard. The physical and mechanical properties including Cobb values, burst index, tensile index, ring crush test (RCT), corrugated medium test (CMT), and corrugated crush test (CCT) were analyzed. Additionally, the chemical structure of the coated and uncoated papers was studied using Fourier-transform infrared spectroscopy (FTIR). CMC-coated papers exhibited significantly higher RCT, CMT, and CCT values compared to the uncoated samples. Furthermore, PLA hydrophobic characteristics significantly reduced water absorption, as reflected by lower Cobb values in coated samples. The combined PLA-CMC coating substantially enhanced both barrier and mechanical properties compared to uncoated samples. FTIR analysis confirmed chemical modifications in the cellulose matrix as a result of the coating process. These results confirmed that coating of the recycled packaging papers with combined CMC and PLA is a viable approach to improve their strength and water resistance, thereby supporting their potential use in sustainable packaging applications.*

KEYWORDS: *recycled papers; barrier properties; plastic alternatives; biodegradable; mechanical properties*

SAŽETAK • *U ovoj je studiji istražen utjecaj premaza od polilaktične kiseline (PLA) i karboksimetil-celuloze (CMC) na mehanička i fizička svojstva recikliranoga ambalažnog papira. Uzorci papira proizvedeni su prema standardu TAPPI T205-SP-02 iskorištenjem otpadnoga uredskog papira i staroga valovitog kartona. Analizirana su fizička i mehanička svojstva, uključujući Cobbove vrijednosti, indeks probijanja, vlačni indeks, tlačnu čvrstoću prstena (RCT), tlačnu čvrstoću papira s valovitom srednjicom (CMT) i tlačnu čvrstoću valovitog papira (CCT). Dodatno, kemijska struktura premazanoga i nepremazanog papira proučavana je uz pomoć Fourierove infracrvene spektroskopije (FTIR). Papiri premazani CMC-om pokazali su značajno više vrijednosti RCT-a, CMT-a i CCT-a od nepremazanih uzoraka. Nadalje, hidrofobna obilježja PLA-a znatno su pridonijela smanjenju upijanja vode, što se odražava nižim Cobbovim vrijednostima premazanih uzoraka. Kombinirani PLA-CMC premaz znatno*

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je poboljšao hidrofobna i mehanička svojstva u usporedbi s nepremazanim uzorcima. FTIR analiza potvrdila je kemijske modifikacije u celuloznoj matrici kao učinak procesa premazivanja. Ti su rezultati potvrdili da je premazivanje recikliranih ambalažnih papira kombinacijom CMC-a i PLA-a održiv pristup za poboljšanje njihove čvrstoće i otpornosti na vodu, što upućuje na njihovu potencijalnu upotrebu u održivim postupcima pakiranja.

KLJUČNE RIJEČI: *reciklirani papiri; zaštitna svojstva; alternative plastici; biorazgradivost; mehanička svojstva*

1 INTRODUCTION
1. UVOD

The growing environmental issues associated with plastic consumption highlight the essential requirement to substitute traditional plastics with eco-friendly and biodegradable alternatives.

Due to their high durability and resistance to degradation, plastics can persist in the environment for hundreds of years, contributing to long-term pollution of terrestrial and aquatic ecosystems. Microplastics, which result from the fragmentation of larger plastic items, have been detected in oceans, soils, and even in human tissues, raising serious concerns about their potential toxicological impacts (Andrady, 2011). Additionally, the production of plastics relies heavily on fossil fuels, which exacerbates carbon emissions and accelerates climate change. Among various candidates, paper-based packaging has emerged as a promising solution due to its low cost, renewable origin, biodegradability, recyclability, and lightweight nature. Consequently, extensive efforts have been focused on utilizing paper as a sustainable packaging material (Gällstedt *et al*., 2005).

One critical limitation of paper is its intrinsic hydrophilicity, resulting from the abundance of hydroxyl groups in cellulose, which compromises its performance under humid conditions. Consequently, enhancing the moisture resistance of paper without undermining its recyclability has become a focal point in sustainable packaging research. (Taboada Rodrigues *et al*., 2013). Furthermore, due to increased environmental regulations, which limit the utilization of wood-derived resource, packaging papers are made from 80 – 100 % recycled fibers (Cicekler *et al*., 2024). Papers made from recycled fibers exhibit lower mechanical strength and moisture resistance compared to those produced from virgin fibers. Therefore, if recycled papers are to be used as packaging materials, their properties must be seriously reinforced. In recent years, considerable attention has been directed toward the development of coatings that improve the barrier and mechanical properties of paper while maintaining its environmental compatibility. (Cicekler *et al*., 2024). However, many conventional coating materials are derived from synthetic plastics, which have negative impact on the biodegradability and recyclability of paper. This has led to growing interest in the development and utilization of bio-based coatings (Mazhari Mousavi *et al*., 2017; Taboada Rodrigues *et al*., 2013).

Various sustainable and biodegradable materials have been investigated as substitution of synthetic polymer coatings (Taboada Rodrigues *et al*., 2013; Kunam *et al*., 2024). Polylactic acid shows excellent barrier properties, effective film-forming capabilities, and strong interactions with cellulosic materials due to its semi-hydrophilic character (Sundar *et al*., 2020; Taboada Rodrigues *et al*., 2013; Kamthai and Magraphan, 2018; Rivero *et al*., 2017). The previous studies showed that the PLA coated paper has good barrier properties against water and water vapor. Nonetheless, its inherent brittleness restricts its application in flexible packaging (Zhang *et al*., 2020).

To overcome this problem, various solutions including the utilization of plasticizers, additives, combining with other polymers, and optimization of crystallization conditions have been proposed (Cabedo *et al*., 2006). One of the materials that can improve the properties of polylactic acid is carboxymethyl cellulose, which has suitable properties for papermaking due to the presence of cellulose in its structure and its ability to disperse fibers and reduce their flocculation.

CMC is produced by introducing the carboxymethyl groups along the cellulose chain. CMC has been used in textiles, cosmetic and food industries (Mazhari Mousavi *et al*., 2017). It is inexpensive and readily available (Chen *et al*., 2016; Mazhari Mousavi *et al*., 2017; Kamthai and Magraphan, 2018).

Due to its excellent film-forming ability, water retention properties, and high solubility, CMC is widely used as a surface-sizing agent, coating binder, and wet-end additive in the papermaking industry. (Beghello *et al*., 1997; Blomstedt, 2007). It not only improves the mechanical integrity of paper but can also mitigate the stiffness of PLA, enhancing its flexibility. (Kamthai and Magraphan, 2018).

Chen *et al*. (2015) investigated the biocomposites prepared from PLA and CMC by ionic assembly. They found that the biocomposite formed a transparent and uniform coating layer after casting. Both the modulus of elasticity and the maximum degradation temperature of PLA/CMC composites increased with the decrease in molecular weight of PDMAEA. Although the combination of polylactic acid (PLA) and carboxymethyl cellulose (CMC) has been previously explored in the development of composite materials, their application as a coating system for packaging paper has not yet been thoroughly investigated. Considering the advantageous properties of both substances as potential coating agents, this combination may offer a promising and sustainable alternative for enhancing the performance of recycled paper-based packaging.

Therefore, the present study aims to investigate the effects of PLA, CMC, and their combination as surface coatings on recycled packaging papers. The primary objective is to evaluate their influence on key mechanical properties and water resistance, with the broader goal of identifying eco-friendly coating strategies suitable for industrial applications in sustainable packaging.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Materials
2.1. Materijali

PLA (commercial grade 4042D; Mw = 154.8 kg/mol) was purchased from Rayan Polymer Arta Co. (Iran). Carboxymethyl cellulose (CMC) with a molecular weight of 250,000 g/mol and a degree of substitution (DS) of 1.2 was obtained from Ovj Azma Plast Co. (Iran). Methylene dichloride (CH_2Cl_2, analytical grade) was used as the solvent and supplied by Ghatran Chimi Tajhiz (Iran). Waste office paper (WOP) and old corrugated cardboard (OCC) served as sources of recycled paper fibers.

2.2 Manufacturing of recycled paper
2.2. Proizvodnja recikliranog papira

Paper samples were prepared using a 50:50 ratio of OCC and WOP, as well as 100 % OCC. The fibers were processed in a pulper, and sheets were formed according to the TAPPI T205 SP-02 standard, with a grammage of 127 g/m².

2.3 Preparation and application of coatings
2.3. Priprema i nanošenje premaza

To prepare the PLA coating, 1g of PLA was dissolved in 100 mL of chloroform and stirred continuously at 40 °C for 12 hours. The CMC solution was prepared by dissolving 1 % (w/v) CMC in distilled water under stirring at 600 rpm for 3 hours at room temperature. For the composite coating (PLA-CMC), equal volumes of the prepared PLA and CMC solutions were mixed gently to ensure uniform dispersion before application. All coatings were applied using a 4-bar laboratory coater, with a fixed blade gap of 50 µm, at a drawdown speed of 30 mm/s. The coatings were applied on the surface of papers manufactured in sequentially two layers. The coated samples were then dried in a vacuum oven at 30 °C for 24 hours (Sundar *et al*., 2020). Table 1 outlines the experimental plan.

Table 1 Experimental design and sample coding
Tablica 1. Postavke eksperimenta i označavanje uzoraka

Sign of treatment *Oznaka tretmana*	**Kind of coating** *Vrsta premaza*	**Kind of fibers** *Vrsta vlakana*	
		100 % OCC (1)	**50 %-50 % OCC+OWP (2)**
Control- 1	Uncoated	1	
Control -2	Uncoated	2	
PLA-CMC-1	PLA+CMC	1	
PLA-CMC-2	PLA+CMC	2	
PLA-1	PLA	1	
PLA-2	PLA	2	
CMC-1	CMC	1	
CMC-2	CMC	2	

OCC – Old corrugated cardboard; WOP – Waste office paper; PLA – Polylactic acid; CMC – Carboxymethyl cellulose. The coding system includes fiber composition and coating type for each treatment group.
OCC – stari valoviti karton; WOP – otpadni uredski papir; PLA – polilaktična kiselina; CMC – karboksimetil celuloza. Sustavom označavanja obuhvaćen je sastav vlakana i vrsta premaza za svaku skupinu tretmana.

2.4 Measurement of paper properties
2.4. Mjerenje svojstava papira

All samples were conditioned at 25 °C and 65 % relative humidity for 24 hours prior to testing. Physical and mechanical properties of coated and uncoated papers were then evaluated using standardized procedures.

Water absorption capacity was measured using a Cobb apparatus according to the TAPPI T441 standard (Cobb test, 30 seconds).

Tensile index and burst index were determined according to ISO 5256-1:1979 and TS 3123 EN ISO 2759, respectively.

Ring Crush Test (RCT), Corrugated Medium Test (CMT), and Corrugated Crush Test (CCT) values were assessed based on TAPPI T822-om-16, T809-om-17, and T824-om-14.

2.5 FTIR analysis of coated papers
2.5. FTIR analiza premazanih papira

The chemical structure of coated papers was characterized using Fourier-transform infrared (FTIR) spectroscopy to detect changes in functional groups caused by surface coatings. The measurements were performed on a PerkinElmer System 2000 spectrometer (Waltham, MA, USA), scanning in the range of 400 – 4000 cm^{-1} at a spectral resolution of 4 cm^{-1}.

2.6 Statistical analysis
2.6. Statistička analiza

The impact of coating on paper properties was analyzed using one-way ANOVA. Duncan's multiple range test was used to determine significant differences in paper properties between treatments.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Table 2 presents the statistical analysis of the coated and uncoated paper samples, demonstrating that all coating treatments significantly influenced paper properties at a 99 % confidence level ($p \leq 0.01$). Duncan's multiple range classification results are presented in Table 3.

The statistical analysis confirms that PLA and CMC coatings significantly enhance the properties of recycled packaging paper ($p \leq 0.01$). Water absorption, determined by Cobb testing, showed a notable reduction across coated samples, with PLA-CMC-2 exhibiting the lowest absorption (82.33 g/m²) versus the uncoated control (105.67 g/m²). This indicates improved moisture resistance due to PLA hydrophobic barrier and CMC surface modification effects. Mechanical strength indicators including burst index, tensile index, and compression resistance (RCT, CMT, and CCT) increased significantly in all coated samples relative to the control groups.

The highest tensile strength was observed in PLA-CMC-2 (41.82 N), significantly surpassing the control (27.73 N), highlighting the role of coatings in enhancing fiber bonding and structural integrity.

The improvements in RCT, CMT, and CCT further support the effectiveness of these coatings in strengthening recycled paper. Higher compression strength values, particularly in CCT (6.03 in PLA-CMC-2 vs. 3.48 in the control), indicate better resistance to stacking and mechanical stress, essential for packaging applications. The combination of PLA and CMC produced the most favorable results across both mechanical and barrier property evaluations. The complementary nature of PLA hydrophobicity and CMC bonding ability created a synergistic effect that improved performance significantly.

Wei *et al*. (2019) and Kamthai and Magaraphan (2018) also observed similar interactions, highlighting how hydrogen bonding and molecular compatibility between PLA and CMC can reinforce structural cohesion and flexibility in coated substrates.

3.1 Water absorption resistance
3.1. Otpornost na upijanje vode

Figure 1 illustrates the effect of coating on Cobb values. The highest water resistance was observed in PLA-1 samples (100 % OCC coated with PLA), whereas the highest water absorption occurred in the Control-1 sample (uncoated 100 % OCC paper). The superior water resistance of PLA-coated samples is attributed to the hydrophobic nature of PLA. Papers coated with a combination of PLA and CMC showed significantly lower Cobb values as compared to uncoated samples. These findings align with Taboada-Rodriguez *et al*. (2013), who reported that PLA coatings drastically reduce water absorption in paper.

Table 2 Statistical analysis of properties of paper samples
Tablica 2. Statistička analiza svojstava uzoraka papira

Properties *Svojstva*	**Sum of squares** *Zbroj kvadrata*	**Mean squares** *Srednja vrijednost kvadrata*	**Df (within groups)** *Df (unutar grupa)*	***F***	**Sig**
Cobb test	3358.36	305.31	11	21.894	0.000
Burst	10536.306	957.846	11	8.365	0.000
Tensile	5.429	0.494	11	8.113	0.000
RCT	8133.889	739.444	11	8.082	0.000
CMT	15041.222	1367.384	11	5.099	0.000
CCT	10536.306	957.846	11	8.365	0.000

Table 3 Average values and Duncan's multiple range classification of properties of paper samples
Tablica 3. Prosječne vrijednosti i Duncanova klasifikacija s višestrukim rasponima za svojstva uzoraka papira

Properties *Svojstva*	**Control-1** *Kontrolna skupina-1*	**Control-2** *Kontrolna skupina-2*	**PLA-CMC-1**	**PLA-CMC-2**	**PLA-1**	**PLA-2**	**CMC-1**	**CMC-2**
Cobb test	105.67 (d)	93 (c)	78.67 (b)	82.33 (bc)	67.67 (a)	74.33 (ab)	74 (ab)	79.67 (b)
Burst	1.93 (d)	1.93 (d)	2.01 (b)	2.04 (a)	2.01 (b)	1.99 (c)	1.98 (c)	1.97 (c)
Tensile	27. 73 (d)	27.76 (d)	36.55 (ab)	41.81 (a)	32.34 (bcd)	30.85 (cd)	33.9 (bc)	29.98 (cd)
RCT	1.63 (ab)	1.61 (d)	1.74 (e)	1.72 (c)	1.79 (b)	1.77 (e)	1.85 (a)	1.83 (ab)
CMT	1.86 (a)	1.88 (a)	1.71 (ab)	1.76 (ab)	1.31 (c)	1.51 (bc)	1.86 (a)	1.9 (a)
CCT	3.48 (d)	3.92 (c)	5.25 (b)	6.03 (a)	5.24 (b)	5.47 (bc)	5.23 (b)	5.6 (bc)

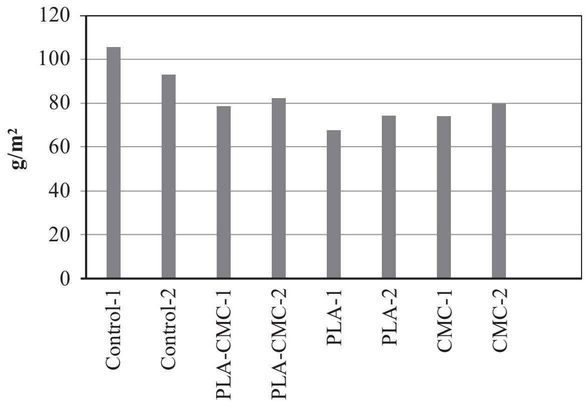

Figure 1 Effect of coating on Cobb values of paper
Slika 1. Utjecaj premaza na Cobbove vrijednosti papira

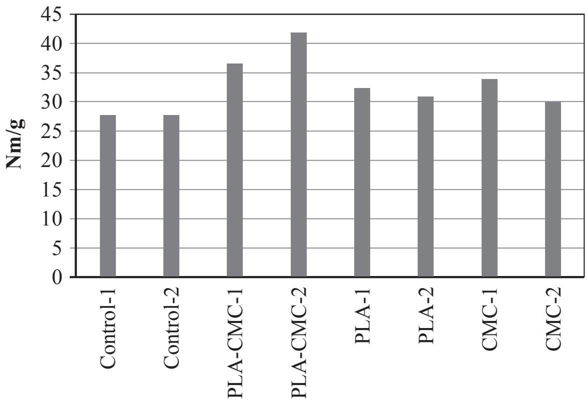

Figure 3 Effect of coating on tensile index of paper
Slika 3. Utjecaj premaza na vlačni indeks papira

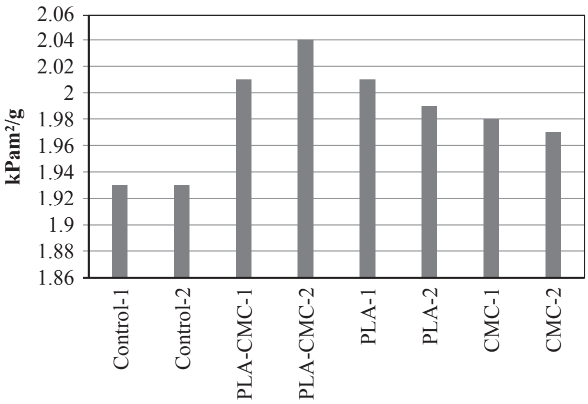

Figure 2 Effect of coating on burst index of paper
Slika 2. Utjecaj premaza na indeks probijanja papira

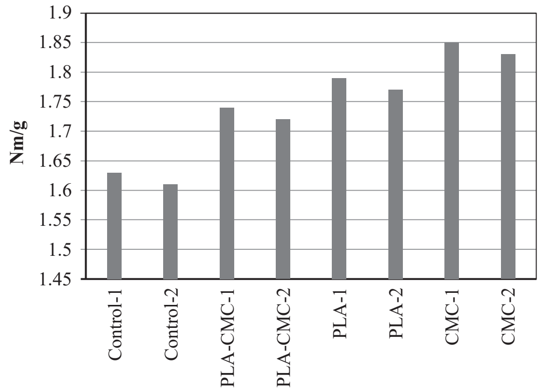

Figure 4 Effect of coating on RCT index of paper
Slika 4. Utjecaj premaza na RCT indeks papira

3.2 Burst index
3.2. Indeks probijanja

Figure 2 shows the burst index results. The highest burst index was observed in PLA-CMC -2 samples, suggesting that the combined coating enhances paper strength.

Improvement of burst index of PLA-CMC-coated packaging paper can be attributed to the synergistic effect of these materials, which leads to enhance fiber bonding, stress distribution, and structural integrity. PLA forms a strong, continuous film that condenses fibers and improves cohesion, while CMC enhances adhesion and flexibility through hydrogen bonding, reinforcing the paper network by reducing weak points, as outlined by Mazhari Mousavi (2017). Consequently, these properties lead to a stronger, coated paper with a higher burst index.

3.3 Tensile index
3.3. Vlačni indeks

Figure 3 shows the tensile index values of the papers. Coated samples have higher tensile index values as compared to uncoated papers. The highest tensile index was observed in PLA-CMC-2 (50 % OCC + 50 % WOP coated with PLA-CMC). These results are in accordance with a previous study, which revealed that PLA coatings improved the tensile index by approximately 33 % (Abuzeid *et al.*, 2017). The improvement of tensile index is related to the presence of carboxyl groups in CMC, which can enhance fiber bonding (Laine *et al.*, 2003; Kamthai and Magraphan, 2018).

The results of the Cobb, burst, and tensile tests reveal interrelated improvements in the paper performance characteristics. The reduction in water absorption (Cobb test) contributes to maintaining fiber integrity and bonding, which directly enhances mechanical properties such as burst and tensile strength. This interdependence indicates that the coatings not only provide a moisture barrier but also synergistically strengthen the fiber network, leading to comprehensive enhancement of both barrier and mechanical functions of the recycled paper (Laine *et al.*, 2003).

3.4 Ring crush test (RCT) index
3.4. Ispitivanje indeksa tlačne čvrstoće prstena (RCT)

As shown in Figure 4, coated papers have increased RCT values. The highest RCT value was related to CMC-1 (100 % OCC coated with CMC).

CMC acts as a dry-strength additive, forming hydrogen bonds with cellulose fibers, which increases fiber-to-fiber interaction and improves the overall mechanical integrity of the paper (Beghello *et al.*, 1997; Blomstedt *et al.*, 2007). Additionally, CMC enhances fiber swelling and flexibility, allowing better fiber entanglement, which contributes to higher resistance against compressive forces (Laine *et al*., 2003). CMC also helps in fiber surface modification, improving stress distribution and reducing weak points within the paper matrix (Mazhari Mousavi *et al*., 2017).

3.5 Corrugated medium test (CMT) index
3.5. Ispitivanje indeksa čvrstoće papira s valovitom srednjicom (CMT)

Figure 5 demonstrates that CMC-1 samples had the highest CMT index. However, PLA coatings resulted in a decrease in CMT values. The relationship between CMT strength and paper stiffness has been established in previous studies (Chen *et al*., 2001; Cicekler *et al*., 2024). The addition of CMC improves tensile, tear, and surface strength while reducing roughness (Beghello *et al*., 1997).

One of the limitations of PLA is its brittleness and reduced toughness, which is why various studies have attempted to improve its toughness by adding different materials. (Reisi Pour *et al*., 2018).

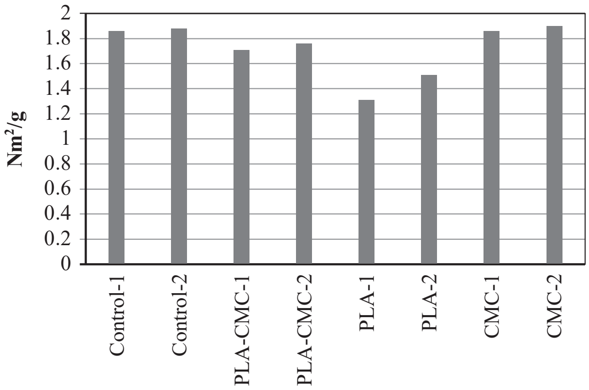

Figure 5 Effect of coating on CMT index of papers
Slika 5. Utjecaj premaza na CMT indeks papira

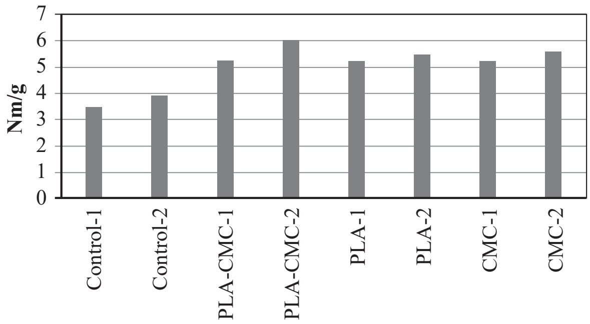

Figure 6 Effect of coating on CCT index of papers
Slika 6. Utjecaj premaza na CCT indeks papira

3.6 Corrugated crush test (CCT) index
3.6. Ispitivanje indeksa tlačne čvrstoće valovitog papira (CCT)

Figure 6 illustrates that PLA-CMC-2 samples exhibited the highest CCT index, while Control-2 had the lowest. The combination of fibers led to improved CCT performance. CCT values are primarily influenced by moisture absorption (Cicekler *et al*., 2024).

Overall, the results indicate that CMC coating has a significant positive impact on improving the quality of recycled packaging paper. CMC can improve fiber strength due to its hydroxyl groups, which promote hydrogen bonding between water and fibers (Enoki, 1999).

Previous studies have shown that PLA coating effectively reduces water absorption while improving the tensile and burst strength of paper (Sundar *et al*., 2020). It is obvious that PLA coating improves packaging paper performance (Rivero *et al*., 2017). The combined use of PLA and CMC as a coating can lead to superior results as compared to individual PLA coating, because of the improved flexibility of PLA when combined with CMC.

3.7 Chemical structure of coated papers
3.7. Kemijska struktura premazanih papira

Figure 7 shows the FTIR spectra of recycled paper coated with PLA, CMC, and their combination. Characteristic absorption bands were observed in the regions of 2800 – 3500 cm^{-1} and 550 – 1650 cm^{-1}, which are typical for cellulosic substrates due to the presence of hydroxyl, carbonyl, and alkyl groups.

A broad and intense band near 3374 cm^{-1} corresponds to the stretching vibration of the O–H bond, confirming the presence of hydroxyl groups in the cellulose structure (Manandhar *et al*., 2022). In CMC-coated papers, intensity increased at 1410 and 1319 cm^{-1} is associated with O–H and C–H stretching, while absorption peaks at 1107 and 1039 cm^{-1} represent C–O stretching vibrations typical of polysaccharides (Rozali *et al*., 2015).

For PLA-coated samples, a distinct absorption peak at 1755 cm^{-1} corresponds to the stretching vibration of the carbonyl (C=O) group in the ester linkage, a key functional group in polylactic acid. A minor but noticeable shift in the C=O stretching band from 1755 cm^{-1} to approximately 1740 cm^{-1} in PLA-coated samples also supports the successful incorporation of carboxyl functional groups, consistent with previous literature (Rivero *et al*., 2017).

Enhanced absorption bands at 2996 and 2945 cm^{-1} are attributed to asymmetric and symmetric C–H stretching vibrations of methyl groups. Additionally, a peak at 1187 cm^{-1} indicates C–O stretching in ester bonds (Singla *et al*., 2012).

In samples coated with both PLA and CMC, evidence of intermolecular hydrogen bonding is observed through the shift of the O–H/N–H stretching band to ~3420 cm^{-1}, along with increased intensity and peak narrowing. These spectral changes confirm the formation of hydrogen bonds between the PLA matrix and the CMC molecules. Notably, the intensity of this peak is lower in pure PLA, suggesting the addition of CMC enhances hydrogen bonding interactions (Wei *et al*., 2019).

These spectral changes suggest that hydrogen bonding and molecular interactions between PLA,

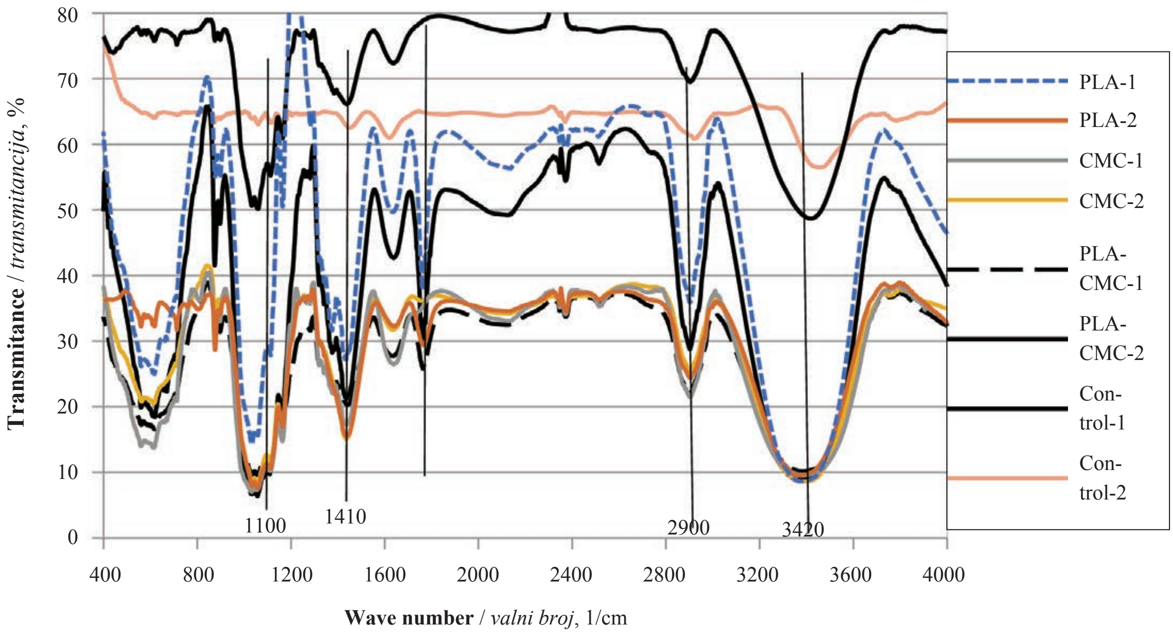

Figure 7 FTIR of paper samples with different coating materials
Slika 7. FTIR uzoraka papira s različitim premaznim materijalima

CMC, and cellulose fibers enhance interfacial adhesion, which likely contributes to the improved mechanical integrity observed in coated samples. The shift and intensity changes in the O–H and C=O regions correlate with increased fiber bonding and reduced water permeability, confirming the functional role of the coatings in modifying paper performance.

The combined use of PLA and CMC as a coating can lead to superior results as compared to individual PLA coating. Recent studies support the claim that incorporating carboxymethyl cellulose (CMC) into polylactic acid (PLA) matrices enhances the flexibility and mechanical performance of the resulting composite. Specifically, Kamthai and Magaraphan (2015) demonstrated that CMC derived from bagasse improved the toughness of PLA-based films. Their FTIR analysis revealed new absorption bands indicative of hydrogen bonding between the hydroxyl groups of CMC and the ester groups of PLA, suggesting intermolecular interactions that contribute to greater flexibility and reduced brittleness. Similar findings were reported by Khalil *et al*. (2020), where PLA–CMC blends exhibited enhanced elongation at break and tensile strength, attributed to improved dispersion and interaction of CMC within the PLA matrix.

In another study, films composed of PLA and sodium carboxymethyl cellulose (NaCMC) designed for pH-responsive applications showed higher swelling capacity and mechanical resilience. FTIR spectra confirmed structural modifications and new interaction bands between PLA and CMC components, further validating the compatibility and synergistic behavior of the blend. Collectively, these findings confirm that the addition of CMC can alter the physical structure of PLA by increasing its amorphous regions and enabling more flexible polymer chains, which are critical for packaging and coating applications where improved ductility is needed.

4 CONCLUSIONS
4. ZAKLJUČAK

This study evaluated the impact of PLA, CMC, and PLA–CMC composite coatings on recycled packaging papers made from OCC and WOP fibers. Papers were produced using two fiber compositions including 100 % OCC and a 50-50 proportion of OCC and WOP.

PLA coatings reduced water absorption due to their hydrophobic characteristics, while CMC improved mechanical integrity, particularly in compression-related properties such as RCT, CMT, and CCT. The combined PLA–CMC coating exhibited the highest values for tensile and burst indices, indicating a synergistic interaction that optimized both flexibility and strength.

The results indicate that carboxymethyl cellulose enhances the flexibility of PLA, leading to better overall paper performance. Additionally, papers made from pure OCC fibers showed better mechanical strength due to the presence of lignin, which increases fiber cohesion.

The innovative combination of polylactic acid (PLA) and carboxymethyl cellulose (CMC) for recycled paper coatings presents a suitable approach to enhancing mechanical and physical properties. This unique blend offers significant potential for industrial applications in sustainable and biodegradable packaging materials, providing an eco-friendly alternative to conventional coatings. Future research should focus on optimizing the coating formulation and process parameters to facilitate large-scale production, as well as evaluating the long-term durability and performance of these coatings under real-world conditions.

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