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Grain by-products and *Saccharomyces cerevisiae* application in paper packaging material: impact on physical–mechanical and barrier properties

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Abstract

Renewable materials and material circularity are key priorities for the coming decades. While paper is the most utilized material in the packaging sector, its applications in food packaging are limited due to low barrier properties. Coating it with petroleum-based polymer barrier coatings renders it unrecyclable both mechanically and biologically. Bio-coated paper packaging, made from agricultural waste or by-products, presents environmentally favorable solutions that can benefit the biological cycle of the circular economy. The main objective of this study is to assess the applicability of grain and beer production by-products in wood pulp food packaging materials. It examines the effects of different grain by-products (industrial wheat grain processing residues and wheat bran) particles and concentrations (15 wt% and 40 wt%), as well as the impact of brewer's yeast (*Saccharomyces cerevisiae*) at a concentration of 10 wt%, on the physical–mechanical and barrier properties of Northern bleached softwood kraft (NBSK) and chemithermomechanical (CTMP) pulps. Material composites were fabricated using a standard sheet forming method. Physical–mechanical properties were analyzed through tensile strength, strain at break, tear resistance, and bending stiffness tests. Barrier-related properties were analyzed through roughness, air permeance, and water contact angle tests. Results revealed that the vast majority of physical–mechanical properties decreased with the increase of both types of grain production fillers. Industrial wheat grain processing residues had a lower impact on physical–mechanical properties than wheat bran filler. A higher percentage of property decrease was absorbed in NBSK pulp than in CTMP. Roughness of CTMP can be improved by adding both industrial wheat grain processing residues and wheat bran. Wheat bran particles can increase hydrophobicity. CTMP pulp strength properties can be increased with the addition of yeast; however, the yeast additive's effect on air permeance demonstrated a negative impact. In the case of NBSK pulp, which has higher primary strength properties, the addition of yeast does not make any significant changes. The conducted experiments demonstrated that, overall, the addition of these fillers resulted in a decline in physical–mechanical properties such as tensile strength, strain at break, tear resistance, and bending stiffness. This decline was more pronounced with higher concentrations of fillers. In the case of CTMP pulp, both types of fillers exhibited similar trends in affecting properties, whereas for NBSK pulp, wheat bran had a more significant impact compared to wheat grain processing residues. The addition of yeast generally led to a reduction in physical–mechanical properties, particularly in tensile strength and tear resistance. However, samples containing yeast displayed increased flexibility compared to controls. The influence on barrier properties varied: while yeast increased air permeability, it also enhanced surface hydrophobicity, thereby reducing the paper's receptivity to liquids.

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1 Introduction

Growing reliance on single-use food packaging and its negative environmental impacts, including plastic and microplastic pollution on ecosystems and human health, as well as its impact on resource depletion and increasing waste, underscores the urgent need for alternatives. Food-contaminated packaging is difficult to clean and therefore challenging to recycle, further emphasizing the necessity for single-use packaging alternatives. Bio-based and biodegradable packaging could serve as one such solution, integrating mechanically unrecyclable food and food packaging materials into circular economy biological recycling systems [1, 2], ultimately resulting in lower environmental impacts [3, 4].

Even though the properties of paper limit its application in food packaging, when coated with natural origin coatings [5–7], paper demonstrates good mechanical and barrier properties [8], while remaining biologically recyclable [9–13]. The consumption of paper production in the coming decade is projected to continue rising by more than 10% [14]. In the context of climate change and forest depletion, it is important to increase non-wood fiber stock. However, the share of other pulp sources in Europe (excluding the Russian Federation), such as sugar cane bagasse, wheat straw, kenaf, cotton rags, and hemp, is only 0.25% (89,000 tonnes out of 35,447,000) [15].

It is known that blending 10–15 wt% of fibers other than wood into wood pulp does not affect the paper production process and can even improve its properties [16]. One of the most efficient solutions with significant environmental benefits is the utilization of locally available alternative feedstocks, such as agricultural waste and side streams of agricultural production [3], for applications in compostable fast food packaging [17]. In the EU, natural fiber feedstock generated from wheat holds great potential. Wheat and spelt yield in 2021 was 129.9 million tonnes, equivalent to 43.7% of all cereal grains harvested [18]. Grain production residues such as straw, bran, and other lignocellulosic industrial waste, due to their chemical composition, are highly promising sources for non-wood paper or blends of wood and non-wood paper production [17].

Paper is a highly hydrophilic material and, in the case of food packaging, requires additional barrier coatings or additives to increase hydrophobicity. Moisture and oxygen barrier properties of paper packaging are typically enhanced using coatings made of conventional plastics, waxes, ethylene vinyl alcohol (EVOH), and polyvinylidene chloride (PVDC) [8]. Polyethylene (PE) is the most commonly used barrier coating, but its fossil-fuel origin poses environmental concerns, as it can cause microplastic pollution when subjected to biological treatment at the end of its life or through leakage into the environment [19].

Barrier-related properties such as air permeability and hydrophobicity of fully green compostable food packaging can be improved by utilizing bio-origin coatings [20]. Biopolymers for films and coatings can be derived from biomass, synthesized, or directly produced by microorganisms. Protein is a raw material commonly used for bio-based barrier films and coatings, with sources including plants (soy protein, zein, gluten) or animals (fish protein, collagen, casein) [21].

Bakers' and brewers' yeast (*Saccharomyces cerevisiae*) represent another protein-rich source containing 32%–62% protein [22]. Yeast obtained from the beer manufacturing process contains 49% protein [23]. However, yeast as a raw material for barrier coatings application has not yet been thoroughly investigated.

This study represents an experimental stage of previous research on fully green compostable food packaging, crafted from locally available raw materials and industrial by-products within the Baltic Sea region [1, 17]. As previously uncovered: (a) Compostable food packaging holds the potential to add significant value to the circular economy by cleansing waste streams, capturing and diverting food waste from landfills, and serving as mechanically nonrecyclable packaging alternatives that complement the mechanosphere cycle with the biosphere. Additionally, it facilitates the return of biomaterials to the soil, thereby offering various advantages associated with biological recycling; (b) The application of plant-origin feedstocks in food packaging, as well as other sectors, underscores the importance of these feedstocks being renewable and possessing a lower environmental footprint, particularly when utilizing waste or by-products; (c) The tree-free paper market is anticipated to expand, indicating a heightened demand for fully green packaging within the food sector; and (d) Nonetheless, paper applications (both wood and non-wood fiber) in fully green packaging remain limited due to the stringent requirements of barrier properties.

Therefore, the aim of this paper is to investigate:

i. The commercial viability of natural fiber feedstocks and the application of industrial by-products available in the Baltic Sea region, such as wheat bran and industrial wheat grain processing residues, in paper packaging production.
ii. The impact of added brewer's yeast on paper barrier properties.
iii. The effects of natural fiber fillers and yeast on the physical–mechanical properties of paper.

In this study, paper blends containing 15 wt% and 40 wt% of wheat bran and grain processing residues fillers, along with 10% of dry mass *Saccharomyces cerevisiae*, were created. Subsequently, the physical–mechanical and barrier properties of the materials were tested.

2 Materials and methods

2.1 Materials

Northern bleached softwood kraft (NBSK) pulp, produced from pine and spruce, was acquired from Billerud (Solna, Sweden), while chemithermomechanical pulp (CTMP) produced from poplar was obtained from Sicem Saga (Reggio Emilia, Italy). Both pulps are certified by the Forest Stewardship Council (FSC) and suitable for food contact packaging. The physical properties of the pulps, as provided in the manufacturers' technical data sheets, are listed in Table 1.

Industrial wheat grain processing residues, containing wheat, rye, spelt husks, small grains, straw, grass seeds (oats, buckwheat, wild buckwheat), grain dust, and wheat bran (the outer hull of the wheat kernel), were purchased from Malsena Plius (Vievis, Lithuania). Dry brewing yeast (*Saccharomyces cerevisiae*) SafAle™ S-33 was procured from Fermentis (Marquette-lez-Lille, France), while dry sugar was obtained from Nordic Sugar (Kėdainiai, Lithuania).

2.2 Dry content and agricultural residues fraction analysis

Materials' dry content analysis was determined using the rapid moisture analyzer Precisa 310 M/HA300. The composition of industrial grain processing residues and wheat bran fractions was determined using 500 μm, 250 μm, 150 μm, and 75 μm sieves, and the different fractions were weighed using laboratory scales with a resolution of 0.01 g. The original filler composition in paper production was utilized.

2.3 Pulp, agricultural residues pre-treatment and yeast cultivation

A pulp disintegration process of 10,000 revolutions for 5 min was conducted following ISO 5263-1 standard. Additionally, in accordance with producer recommendations to prevent pulp latency alterations, CTMP pulp was soaked in 40 °C water for 20 min. Subsequently, a pulp beating process of 10,000 revolutions for 30 min was carried out following ISO 5264-1 guidelines.

To simulate the brewing process [24, 25], achieve biochemical stabilization, sterilize agricultural residues, and eliminate bacteria, grain processing residues and wheat bran were boiled for 10 min at 100 °C [26, 27]. Dry brewing yeast (*Saccharomyces cerevisiae*) was cultivated in a highly diluted pulp, sterilized agricultural residues, and dry sugar suspension at 23 °C for 14 h. The optimal temperature range for SafAle™ S-33 is 18–26 °C. The ratio of dry mass of pulp-residues mixture, sugar, and yeast was maintained at 10:2.6:1 [28].

Table 1 Physical used pulps properties

Property	unit	CTMP	NBSK
Fiber length	mm	1.5	1.9–2.1
Tensile index	Nm/g	min 25	110
Burst index	kPa m^2/g	1.2	8.2
Tear index	mN m^2/g	6.8	8.5

2.4 Sheet forming and drying

A total of 23 samples with varying compositions of pulp, containing 15 wt% or 40 wt% agricultural residue filler, with or without added yeast corresponding to 10 wt% of the dry mass of pure pulp and/or pulp-agricultural residue mix, were prepared using the conventional sheet-former method outlined in ISO 5269-1:2005. For the preparation of laboratory sheets, the final stock (pure pulp and/or pulp and agricultural residue mixture) was diluted to a consistency ranging from 5 to 2 g/l. Test sheets with a basis weight of 60 g/m^2 were formed and dried in a fast drier. The actual laboratory sheets were made using a suspension amount corresponding to the target weight achieved, following the conventional sheet-former method.

To assess the risk of yeast flush in the conventional sheet-former method, three additional samples were prepared using the closed-loop sheet-former method (see Table 2). All formed sheets were stacked with drying blotters and pressing plates, followed by wet pressing at 490 kPa for 4 min. To maintain consistent sheet drying conditions and ensure yeast deactivation [29] in samples containing added yeast, all wet pressed sheets were dried in a drying drum for 90 min, with a maximum drum surface temperature of 78 °C achieved.

2.5 Sheet conditioning, trimming and properties testing

After conditioning according to ISO 187, the drum-dried sheets were trimmed to a size of 141 × 141 mm using a cutting device before determining their general characteristics such as basis weight, thickness, and grammage. The grammage of the sheets was determined following ISO 536, and the single-sheet thickness was measured according to ISO 534. Tensile properties were determined following ISO 1924, tearing resistance according to ISO 1974, and bending resistance following ISO 2493-1. Bending stiffness was tested in accordance with ISO 5628.

Additionally, air permeability and roughness results were determined using a Bendtsen tester following ISO 5636 and ISO 8791, respectively. The determination of bending resistance and stiffness was performed following ISO 2493-1. The water hydrophilicity/hydrophobicity was determined according to ISO/TS 14778, with a contact time of 0.1 s. Measurements were conducted on paper sheet samples, specifically targeting water drops on non-particle area, particle area, and random area.

Table 2 Final material composition and sheet former methods used

Final stock (wood pulp and agricultural residues ratio)	Conventional sheet-former method, no added yeast	Conventional sheet-former method, 10% added yeast	Closed loop sheet-former method, no added yeast	Closed loop sheet-former method, 10% added yeast
NBSK plain	NBSK	NBSK Y	NBSK loop	NBSK Y loop
NBSK with grain residues 15 wt%	NBSK W15	NBSK W15Y	–	–
NBSK with wheat bran 15 wt%	NBSK B15	NBSK B15Y	–	NBSK B15Y loop
NBSK with grain residues 40 wt%	NBSK W40	NBSK W40Y	–	–
NBSK with wheat bran 40 wt%	NBSK B 40	NBSK B 40Y	–	–
CTMP plain	CMP	CMP Y	–	–
CTMP with grain residues 15 wt%	CMP W15	CMP W15Y	–	–
CTMP with grain residues 40 wt%	CMP W40	CMP W40Y	–	–
CTMP with wheat bran 15 wt%	CMP B15	CMP B15Y	–	–
CTMP with wheat bran 40 wt%	CMP B40	CMP B40Y	–	–

3 Results and discussion

3.1 Materials dry content and agricultural residues fraction analysis

The results of dry content analysis are presented in Table 3. It was observed that the dry industrial wheat grain processing residues, containing wheat, rye, spelt husks, small grains, straw, grass seeds (oats, buckwheat, wild buckwheat), and grain dust, exhibited the highest initial moisture content, nearly 13%. This agricultural residue filler displayed a wider particle fraction distribution compared to wheat bran. The highest proportion of industrial wheat grain processing residues comprised particles larger than 500 µm, with the second-largest share being particles sized between 499 and 250 µm, accounting for 43.9% and 23.9%, respectively. Conversely, the majority of wheat bran-99.9%-consisted of particles larger than 500 µm. The composition of both agricultural residue fillers is provided in Table 4, and the sieved fractions are illustrated in Fig. 1.

Table 3 Material dry content, %

Material	Dry content %
Northern bleached softwood kraft (NBSK)	93.55
Chemithermomechanical pulp (CTMP)	91.1
Industrial wheat grain processing residues	87.25
Wheat bran	92.54
Dry brewing yeasts (*Saccharomyces cerevisiae*)	98.78
Dry sugar	99.89

Table 4 Industrial grain processing residues fraction composition, %

Material	500 µm	250 µm	150 µm	75 µm	˃75 µm
Industrial wheat grain processing residues fraction, %	43.9	23.9	11.6	12.4	8.3
Wheat bran fraction, %	99.5	0.4	0.1	–	–

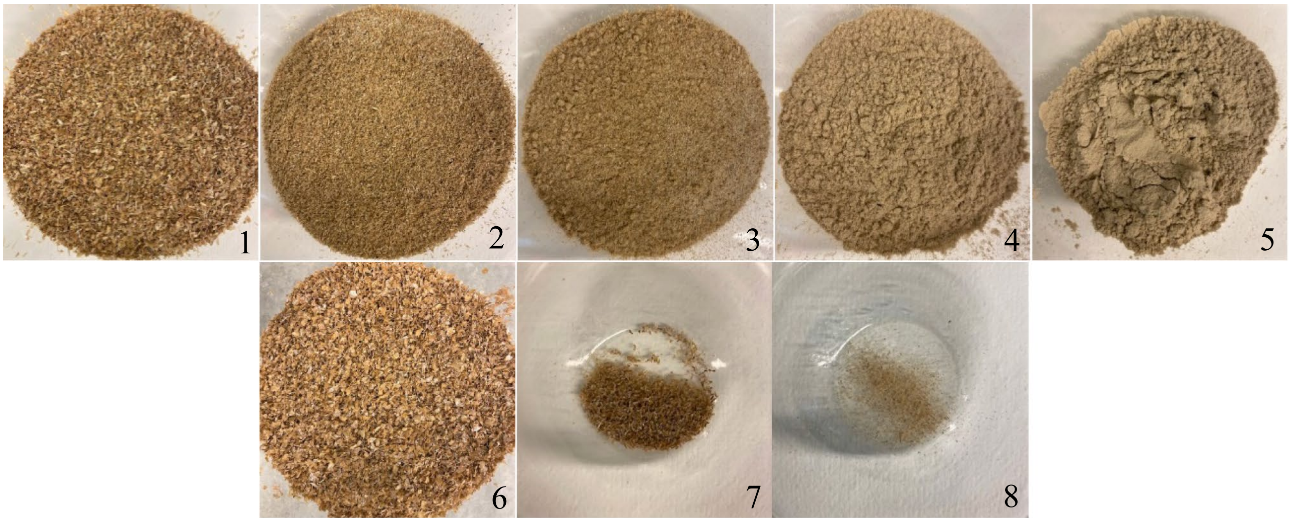

Fig. 1 1–5 sieved industrial wheat grain processing residues fractions, 6–8 wheat bran fractions

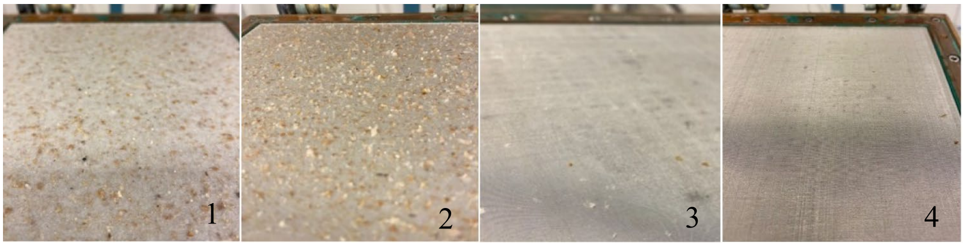

Fig. 2 1, 2–upper/non-wire paper sheet samples surface before removal from sheet former. 3, 4–agricultural residues and pulp leftovers after paper sheet removal

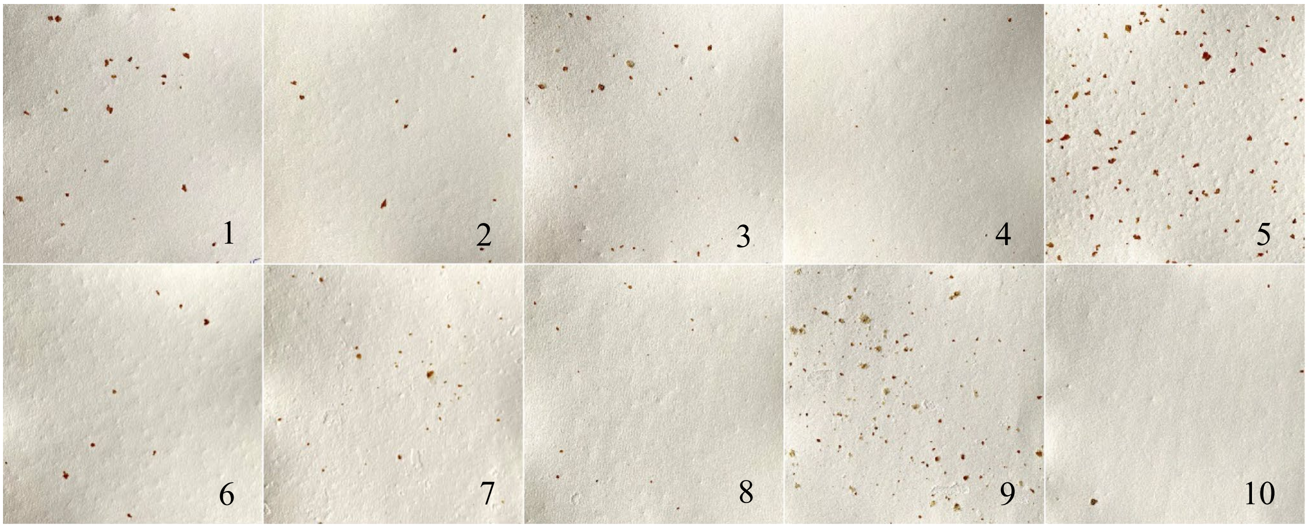

Fig. 3 1, 2 paper sheet samples filed with 15 wt% wheat bran (wire side and non-wire side); 3,4 paper sheet samples filed with 15 wt% industrial wheat grain processing residues (wire side and non-wire side); 5,6 paper sheet samples filed with 40 wt% wheat bran (wire side and non-wire side); 7,8 paper sheet samples filed with 40 wt% industrial wheat grain processing residues (wire side and non-wire side); 9,10 CTMP filed with 40 wt% industrial wheat grain processing residues

3.2 General paper sheet characteristics: grammage and thickness

3.2.1 Grammage

Paper grammage (basis weight) is typically measured by calculating the weight per unit surface area. In this study, the average grammage of 20 tested samples of NBSK pulp was found to be 64.3 g/m^2, while for CTMP pulp, it was 65.33 g/m^2. The minimum and maximum grammage values for NBSK pulp filled with industrial residues were recorded as 64.1 g/m^2 and 67.32 g/m^2, respectively. For filled NBSK pulp, the grammage ranged from 64.58 g/m^2 to 70.05 g/m^2. Grammage variation was attributed to the presence of agricultural residues and pulp loss during sheet removal (refer to Fig. 2) and the drying process. Notably, cellulose-based blotting papers bonded some agricultural residue particles, as depicted in Fig. 3. Due to the protruding surface of the agricultural residue particles, more residue was absorbed onto the blotting paper attached to the non-wire side of the paper sheet (see 1 and 2 in Fig. 2).

CTMP pulp with the addition of 40 wt% industrial wheat grain processing residues was eliminated from further testing due to surface damage during blotting paper removal after the sheet drying process To maintain consistent sheet drying conditions and ensure yeast deactivation [29] in samples containing added yeast, all wet pressed sheets were dried in a drying drum for 90 min, with a maximum drum surface temperature of 78 °C achieved. However, CTMP samples filled with 15 wt% of industrial wheat grain processing residues, 15 wt% and 40 wt% wheat bran fillers, as well as NBSK samples with both additives of 15 wt% and 40 wt% agricultural residues, were tested further as the paper sheet surface after sheet removal and the drying process was not significantly damaged.

In comparing samples with and without added yeast, there was no significant difference observed in paper grammage, thickness, or particle leftovers on blotting paper. The presence of yeast neither strengthened nor weakened the bonds between pulp and agricultural particles.

3.2.2 Thickness

The average thickness of 20 tested samples of plain NBSK pulp was 121 µm, while for CTMP pulp, it was 228 µm. The thickness of filled NBSK samples varied from 117 µm up to 202 µm, with the maximum thickness observed in bran-filled paper samples. This is attributed to the large amount of bran particles (> 500 µm). For CTMP with additives, pulp thickness ranged from 224 µm to 261 µm. Similar to CTMP samples, the maximum thickness was found in bran-filled paper samples. The summary of paper sheet grammage and thickness results is provided in Fig. 4. A detailed laboratory paper sheets tear resistance testing result are provided in figure 4.

In comparison of samples with and without yeast additive, there was an average decrease of 7% in tear resistance in paper samples with yeast additive, except for plain NBSK and NBSK with 15 wt% bran agricultural filler, where there was an average increase of 4%.

3.3 Strength properties

3.3.1 Tensile strength

The tensile strength is the maximum force that the paper will withstand before breaking [30]. Plain NBSK laboratory sheets produced in a closed-loop were characterized by the best strength properties, followed by plain NBSK sheets produced using the regular sheet forming production method. It is known that fines have a positive impact on most strength properties, and they also reduce the air permeability and the porosity of the sheet [31, 32]. The smallest cellulose and filler particles in a regular sheet forming process were flushed out, whereas in a closed-loop process, nanoparticles remained throughout all laboratory sheet production cycles. The performed testing revealed that the tensile strength decreased with the increase of both–industrial wheat grain processing residues and wheat bran–filling agents. NBSK paper tensile strength with the addition of 15 wt% of industrial wheat grain processing residues decreased by 24% and in comparison with 40 wt% bran filler decreased almost twice–by 40% from average of 4.69 kN/m to 2.8 kN/m. Wheat bran additive decreased tensile properties even more by 31%, from 4.69 kN/m to 3.2 kN/m and by 55% or 2.1 kN/m if filled with 40 wt% of agent.

The comparison of NBSK and CTMP sheets shows drastically lower tensile properties mainly due to the fiber characteristics–long fibers from chemical pulp make it possible to have good bonding and hence a high elastic modulus [33, 34]. On the other hand, lignin content and short CTMP fibers affect the tensile strength and elongation of single fibers as well as tensile strength considerably [35]. The plain laboratory sheets' tensile strength of NBSK and CTMP was 4.64 kN/m and 1.01 kN/m, respectively.

With the addition of agricultural residues fillers, tensile properties decreased in all of the samples except CTMP with added yeast–yeast additive increased tensile strength by almost 10%–and CTMP with 15 wt% of industrial wheat

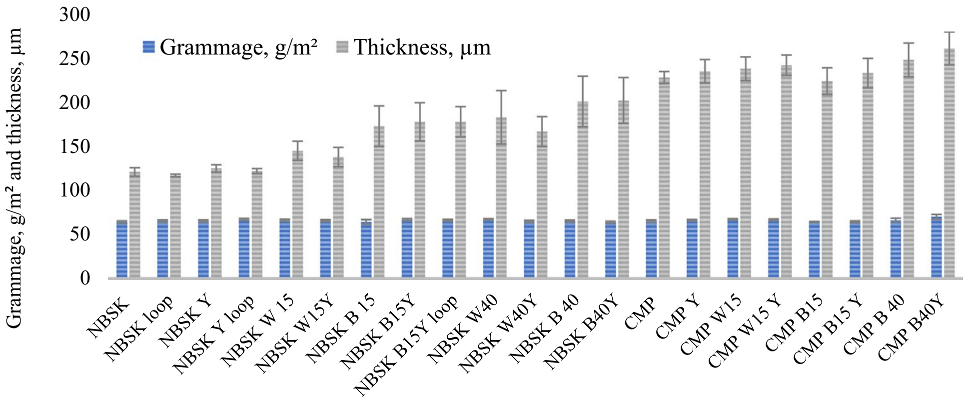

Fig. 4 Laboratory paper sheets grammage and thickness. NBSK (Northern bleached softwood kraft) and CMP (chemithermomechanical) indicates pulp, loop indicated that paper sheets were made in close loop sheet forming system, Y indicates samples with added yeast, W indicates grain residues filler, B indicates wheat bran filler, 15 and 40 wt% of fillers

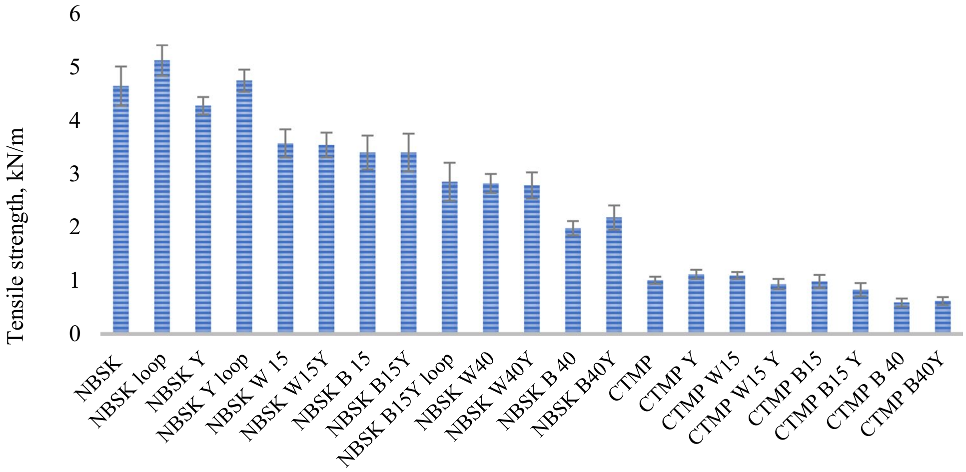

Fig. 5 Laboratory paper sheets tensile strength properties. NBSK (Northern bleached softwood kraft) and CMP (chemithermomechanical) indicates pulp, loop indicated that paper sheets were made in close loop sheet forming system, Y indicates samples with added yeast, W indicates grain residues filler, B indicates wheat bran filler, 15 and 40 wt% of fillers

grain processing residues, which increased strength by 8.9% from 1.01 kN/m to 1.1 kN/m. On average (excluding the sample with CTMP with 15 wt% of industrial wheat grain processing residues), agricultural residues filling agents decreased tensile properties by 9% if added 15 wt% and 39.6% if filled by 40 wt%.

Addition of yeast into NBSK samples W15Y, B15Y, and W40Y did not show any significant difference compared to the same composition materials without added yeast. There was a 10% decrease in tensile properties observed in NBSK B40Y and plain CTMP Y. However, a 15% increase was indicated in CTMP W15Y and CTMP B15Y. All tensile strength testing results are shown in Fig. 5.

3.3.2 Strain at break

Paper extensibility is a critical property for various food packaging applications, including sacks, paper cups, and general food packaging. Enhancing the fiber–fiber bonding contributes to increased extensibility and strength of the paper [36]. The highest mean value of strain at break was observed in NBSK and NBSK with added yeast in the closed loop cycle. Results of the strain break testing are provided in Fig. 6.

In comparison of NBSK samples with 15 wt% and 40 wt% fillers of industrial wheat grain processing residues, if filler proportion is increased from 15 wt% to 40 wt%, the strain at break on average decreases by 10%. For bran filler, the decrease in strain at break properties is 20%. This result, as well as the higher strain at break values in the closed loop cycle, can be explained by the higher content of the smallest cellulose fibers and agricultural particles. The addition of 15 wt% and 40 wt% industrial wheat grain processing residues in NBSK pulp resulted in about a 6% and

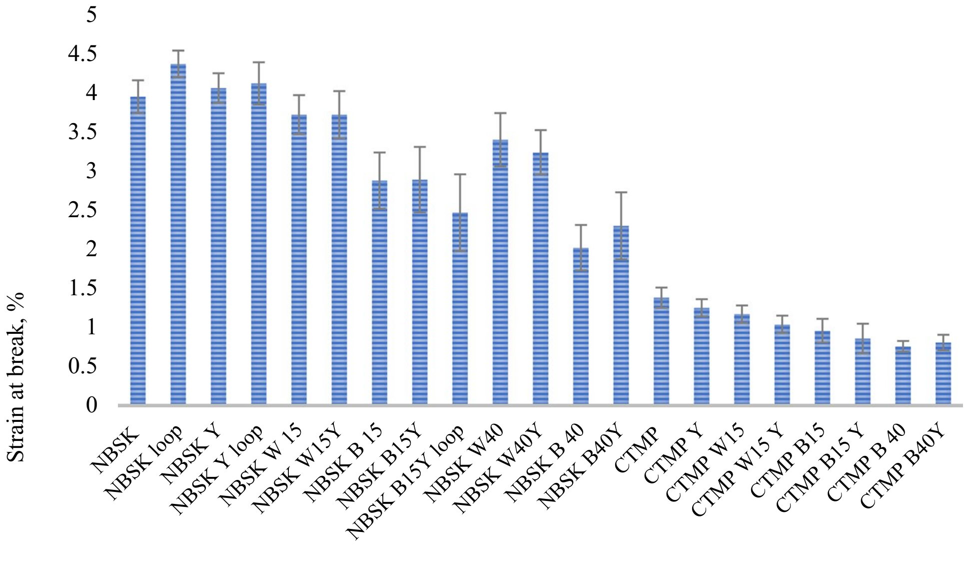

Fig. 6 Laboratory paper sheets strain at break. NBSK (Northern bleached softwood kraft) and CMP (chemithermomechanical) indicates pulp, loop indicated that paper sheets were made in close loop sheet forming system, Y indicates samples with added yeast, W indicates grain residues filler, B indicates wheat bran filler, 15 and 40 wt% of fillers

16% decrease in strain at break, respectively, while wheat bran filler resulted in a 26% and 45% decrease in strain at break, respectively. In CTMP pulp, the addition of 15 wt% industrial wheat grain processing residues additive resulted in a 19% lower strain at break, and for bran additive, it was 34%. Comparing samples with and without yeast additive, there is no significant yeast impact on NBSK pulp samples, while an approximate 10% decrease is observed in CTMP.

3.3.3 Tear resistance

Tear strength of paper refers to the resistance of a sheet of paper to the tearing force it is subjected to. Tear resistance depends on the degree of fiber refinement related to fiber adhesion, fiber strength, fiber length, and quality [37].

The testing revealed that in most cases, the paper tear strength decreased with the increase of both industrial wheat grain processing residues and wheat bran filling agents. The lowest mean value of tear resistance in this test appeared in samples with bran filler. Adding 40 wt% of bran additive in both NBSK and CTMP pulps affected lower tear resistance by approximately 30%. Comparing with 15 wt% bran additives, tear resistance decreased by 14%, from 839 N/mm to 737 N/mm in NBSK, and by 29% to 592 N/mm in CTMP pulp samples.

Industrial wheat grain processing residues filler had a lower impact on paper sheet tear resistance decrease. There was no significant difference in tear resistance in case of 15 wt% additive in NBSK or CTMP pulp, and an 18.8% lower tear resistance with 40 wt% filler of NBSK. Figure 7 as mentioned previously, CTMP with 40 wt% industrial wheat grain processing residues filler was eliminated from further testing due to surface damage to the paper samples.

3.3.4 Bending stiffness

Bending stiffness is a mechanical property that refers to paper rigidity [38] and its resistance against bending, which is related to the modulus of elasticity and thickness. It is crucial for the physical protection packaging function. The bending stiffness depends on the paper thickness and grammage [39]. Stiffness is particularly important in determining the right type of paperboard for packaging applications [34].

Bending resistance is the force required to bend a rectangular paperboard sample through an angle of 15°, while bending stiffness is calculated from the force registered at an angular deflection of 5° [40, 41]. As shown in Fig. 8, the highest mean values of bending stiffness were achieved in CTMP samples. This is partly due to the higher paper thickness—as indicated before, NBSK sample thickness ranged from 117 µm to 202 µm, while CTMP pulp thickness varied from 224 µm to 261 µm [38].

In comparison of samples with different additives, bending stiffness properties decreased with the increase of additives. A significant difference was not observed (only 1.3%) in CTMP pulp when comparing unfilled and filled with 15 wt%

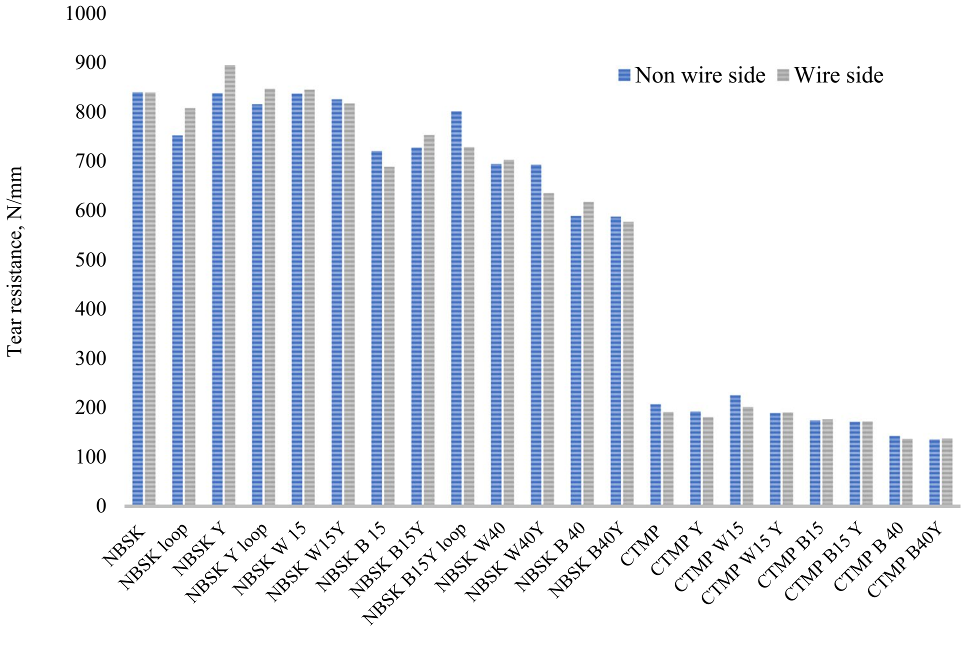

Fig. 7 Laboratory paper sheets tear resistance testing result. NBSK (Northern bleached softwood kraft) and CMP (chemithermomechanical) indicates pulp, loop indicated that paper sheets were made in close loop sheet forming system, Y indicates samples with added yeast, W indicates grain residues filler, B indicates wheat bran filler, 15 and 40 wt% of fillers

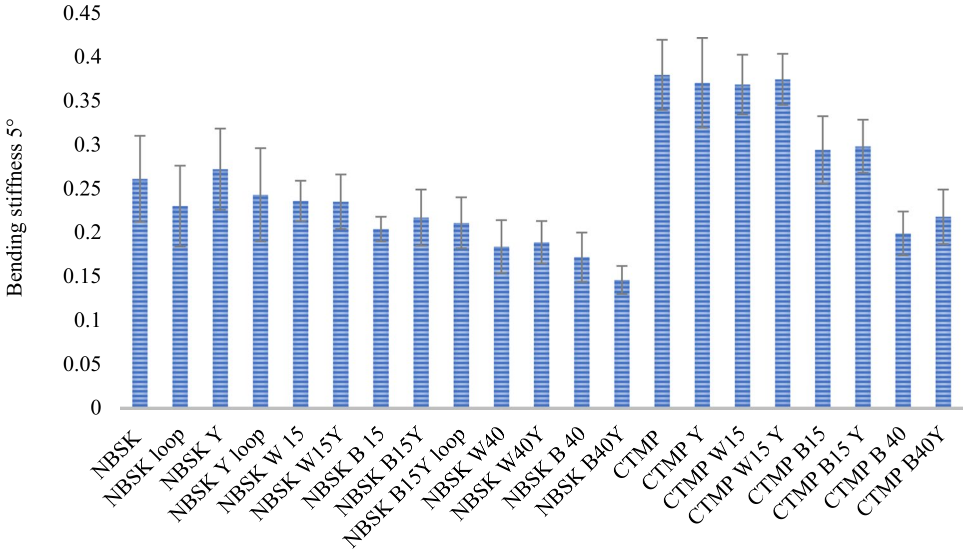

Fig. 8 Laboratory paper sheets stiffness. NBSK (Northern bleached softwood kraft) and CMP (chemithermomechanical) indicates pulp, loop indicated that paper sheets were made in close loop sheet forming system, Y indicates samples with added yeast, W indicates grain residues filler, B indicates wheat bran filler, 15 and 40 wt% of fillers

of industrial wheat grain processing residues additive. However, for other CTMP additives, decreases of 21.3% and 44.5% in bending resistance were found with additives of 15 wt% and 40 wt% bran, respectively.

The decreased bending stiffness of NBSK pulp by 9.1% and 29% resulted from adding 15 wt% and 40 wt% of industrial wheat grain processing residues additive, respectively. Even higher decreases in bending stiffness properties were observed in samples with bran agricultural filler – 21.4% and 43.9%.

In comparison of paper sheets with and without yeast, bending stiffness decreases were observed, indicating reduced resistance to folding or bending and suggesting that the paper becomes less rigid.

3.4 Roughness properties

Paper surface roughness is an important parameter for coated/barrier packaging as it impacts the amount of coating and the choice of coating technology to be used [42]. The result shows the air volume per minute (ml/min) which has leaked out between the probe and the surface. A lower value represents a smoother surface.

It was observed that the lowest initial surface roughness is in plain NBSK pulp with yeast additive produced in a closed loop. In comparison of samples made in standard and closed loop cycle, a 12% less rough surface was achieved when yeast was added in a closed loop. A slight increase in surface smoothness was observed in NBSK paper sheets made with 15 wt% of bran. No significant difference was observed in the standard sheet making method.

In comparison of samples with yeast and without yeast additive, a 25% smoother surface was observed in NBSK with industrial wheat grain processing residues. In other samples, no significant difference was indicated. This leads to a conclusion that a higher yeast (closed loop) and small particle concentration might affect a smoother paper surface.

In regards to samples with agricultural fillers, in most cases, the paper roughness increased with the increase of both industrial wheat grain processing residues and wheat bran filling agents. In comparison of agricultural additives, higher surface smoothness was demonstrated in samples with industrial wheat grain processing residues. This is due to the higher proportion of smaller fraction particles (see Table 4).

In general, due to the protuberant agricultural residues particle surface, higher roughness was observed on the non-wire side (see Fig. 2, samples 1 and 2). The results of NBSK pulp (mean value of wire and non-wire sides) indicated that by adding 15 wt% of industrial wheat grain processing residues and 15 wt% of bran, roughness increased by 69% and 116%, respectively. With the addition of 40 wt% of both fillers, the roughness increased by 135% and 159%, respectively.

In the case of CTMP pulp, the addition of fillers increased surface smoothness. The exception is 40 wt% of bran filler, which had no significant influence. The addition of 15 wt% agricultural filler resulted in a 20% smoother surface in the case of industrial wheat grain processing residues and 19% smoother in the case of bran. Complete data of laboratory paper sheets' roughness testing results are provided in Fig. 9.

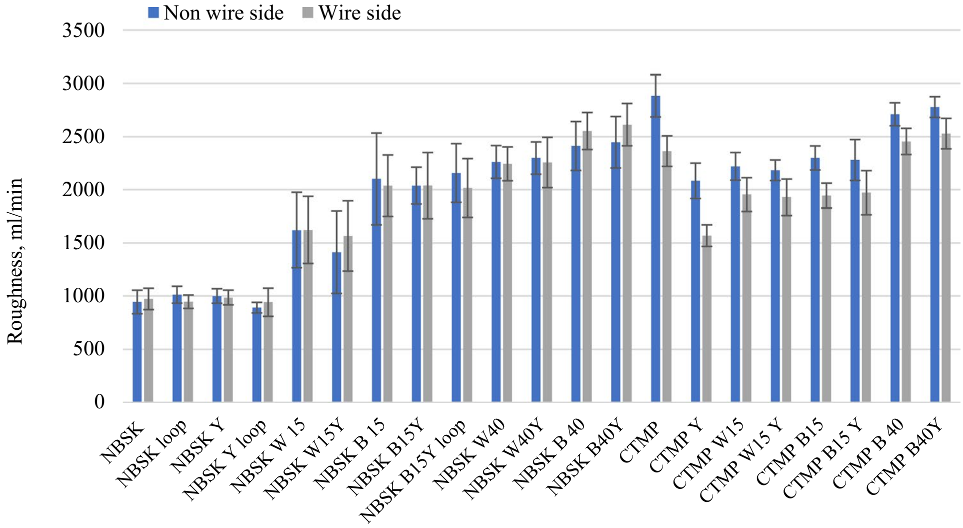

Fig. 9 Laboratory paper sheets roughness testing results. NBSK (Northern bleached softwood kraft) and CMP (chemithermomechanical) indicates pulp, loop indicated that paper sheets were made in close loop sheet forming system, Y indicates samples with added yeast, W indicates grain residues filler, B indicates wheat bran filler, 15 and 40 wt% of fillers

3.5 Barrier properties: air permeance and water contact angle

3.5.1 Air permeance

Air permeance expresses the average volume of air that passes through the material in a minute at elevated pressure [43]. Paper material and cellulose-based packaging, due to the hydrophilicity and porosity of cellulose fiber network, demonstrate weak barrier properties, such as oxygen and water vapor permeability [44].

As a result, all CTMP and NBSK pulp with any agricultural residues additives exceeded 3000 ml/min air permeance and are not presented in Fig. 10.

The lowest initial air permeance was observed in plain NBSK pulp paper sheets made in a closed loop. It demonstrates a 45% higher air permeance compared to the same NBSK pulp sheets made in a standard sheet-making method.

In comparison, yeast-added samples with agricultural fillers showed no significant difference, as all samples mentioned exceeded 3000 ml/min.

In the case of plain pulp samples, the addition of yeast increased air permeance from 1752 ml/min to 3561 ml/min (50.8%) in CTMP and from 2440 ml/min to 3216 ml/min (24%) in NBSK.

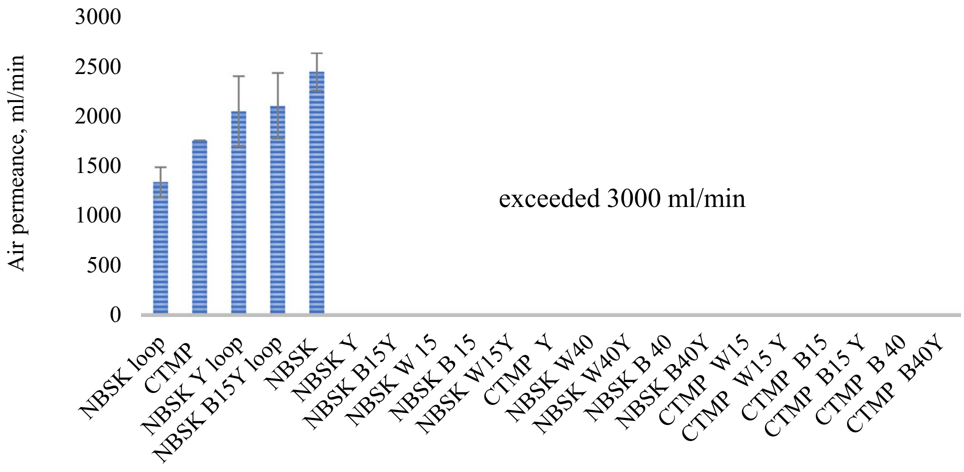

Fig. 10 Laboratory paper sheets air permeance. The measurement range with the device is from 0 to 3000 ml/min. NBSK (Northern bleached softwood kraft) and CMP (chemithermomechanical) indicates pulp, loop indicated that paper sheets were made in close loop sheet forming system, Y indicates samples with added yeast, W indicates grain residues filler, B indicates wheat bran filler, 15 and 40 wt% of fillers

3.5.2 Contact angle

Contact angle (wetting angle) is a value that demonstrates the wettability of cellulose-based material by a liquid [45]. It describes how a liquid is absorbed or spread onto a surface. In the case of complete wetting, the contact angle is 0°. The value between 0° and 90° is described as wettable, and above 90° as not wettable.

During the performed testing, paper sheet samples' hydrophilicity was measured with a contact time of 0.1 s. In order to evaluate both the individual components of the material (pulp and fillers) and the final material composite, contact angle values were measured in different areas: the target particle area, the target plain pulp area, and a random area. Measurements were taken on both the wire side and non-wire side.

The contact angle testing results reveal no significant difference between wire and non-wire sides in the comparison of targeted particle area and area with no particle measurements. The maximum 90° contact angle value was achieved in CTMP B15Y wire side measurement on the targeted particle area. The highest average mean value of the contact angle in this test was also achieved in the same CTMP pulp with 15 wt% of bran and yeast additives, corresponding to 73°. The second-highest average value belongs to CTMP pulp with 40 wt% of bran filler and without yeast, corresponding to 71°.

In specimens with no particles in the target area, the highest average contact angle values of 73° were achieved on both the wire and non-wire sides in CTMP B40Y. For the particle target area and random target area, the highest hydrophobicity properties were observed in CTMP B15Y, corresponding to contact angle values of 82° and 71°, respectively.

The most significant impact of specimen side was observed in samples where the particle target area was measured. The largest differences (highest non-wire side contact angle values compared with wire side) were observed in NBSK B40Y, NBSK W15, NBSK W40, and NBSK B40 samples, with increases from 31° to 46°, from 32° to 43°, from 46° to 62°, and from 50° to 66°, respectively.

In random target areas of specimens, NBSK W40, NBSK B15Y loop, NBSK W40Y, and NBSK B40 wire side contact angle results were higher compared to the non-wire side by 43.38%, 39.86%, 34.52%, and 32.61%, respectively. It is interesting to note that the greatest contact angle difference between the wire and non-wire sides was observed in NBSK Y and NBSK loop specimens, with wire side contact angle values 60.4% and 50.2% higher than those of the non-wire side, respectively. Both wire and non-wire side contact angle measurements are provided in Figs. 11 and 12.

In comparing specimens with and without added yeast, the observed contact angle results indicate that yeast additive increases the surface hydrophobicity of the material. The most significant increase in contact angle value, from 22° to 72°, was observed in plain NBSK pulp produced in a closed loop cycle upon adding yeast. Importantly, when the standard sheet production method was used, the contact angle value decreased from 33° to 21° after adding yeast. This suggests that the increase in material hydrophobicity properties may be attributed to the interaction between yeast and cellulose fines.

The overall summary of paper average values of laboratory sheet testing results is provided in Table 5.

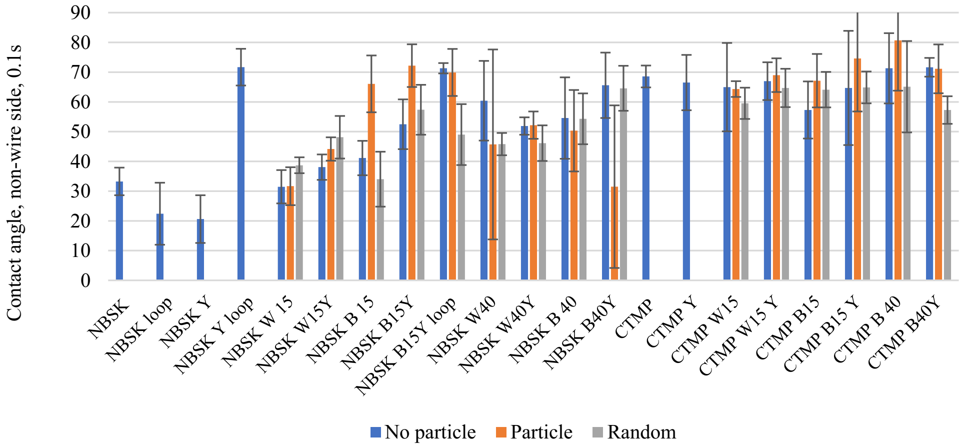

Fig. 11 Laboratory paper sheets contact angle testing results of non-wire side, 0.1 s. NBSK (Northern bleached softwood kraft) and CMP (chemithermomechanical) indicates pulp, loop indicated that paper sheets were made in close loop sheet forming system, Y indicates samples with added yeast, W indicates grain residues filler, B indicates wheat bran filler, 15 and 40 wt% of fillers

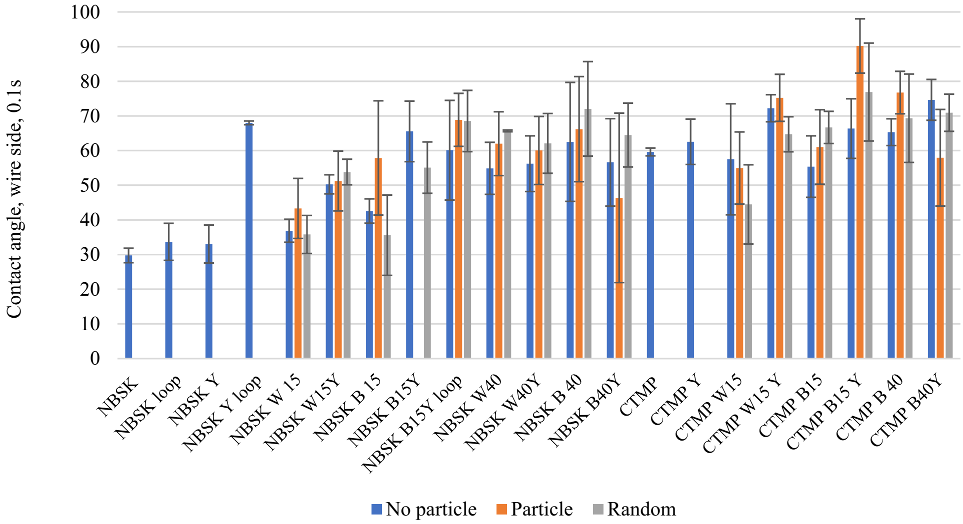

Fig. 12 Contact angle testing results of wire side, 0.1 s. NBSK (Northern bleached softwood kraft) and CMP (chemithermomechanical) indicates pulp, loop indicated that paper sheets were made in close loop sheet forming system, Y indicates samples with added yeast, W indicates grain residues filler, B indicates wheat bran filler, 15 and 40 wt% of fillers

Table 5 Testing result summary: plain CTMP and NBSK–control samples

Sample	General characteristics		Physical-mechanical properties					Barrier properties	
	Grammage, g/m²	Thickness, µm	Tensile strength, kN/m	Strain at break, %	Tear resistance, N/mm	Bending, mN	Stiffness, mN	Air perm., µm / Pa-s	Contact angle, °
CTMP (control)	***65.33***	***228***	***1.01***	***1.38***	***199***	***96.30***	***0.38***	***1752***	***64.10***
CTMP B15	64.63	224	0.99	0.96	175	76.50	0.29	exceeded	61.94
CTMP B15Y	64.58	233	0.83	0.86	172	75.10	0.30	exceeded	72.94
CTMP B40	66.50	248	0.59	0.76	140	51.10	0.20	exceeded	71.42
CTMP B40Y	70.05	261	0.62	0.81	137	55.70	0.22	exceeded	67.25
CTMP W15	67.42	238	1.10	1.17	213	94.70	0.37	exceeded	57.62
CTMP W15Y	66.88	242	0.94	1.04	189	95.20	0.37	exceeded	68.80
CTMP Y	66.38	235	1.12	1.25	186	95.30	0.37	exceeded	64.53
NBSK (control)	***64.30***	***121***	***4.64***	***3.95***	***839***	***70.60***	***0.26***	***2441***	***31.50***
NBSK B15	64.58	173	3.40	2.88	705	53.10	0.20	exceeded	46.20
NBSK B15Y	67.05	178	3.40	2.89	740	57.80	0.22	exceeded	50.45
NBSK B15Y loop	66.30	178	2.85	2.47	765	55.10	0.21	2100	64.63
NBSK B40	65.33	201	1.98	2.02	603	41.80	0.17	exceeded	59.99
NBSK B40Y	64.10	202	2.18	2.30	582	37.30	0.15	exceeded	54.85
NBSK loop	65.40	117	5.12	4.37	780	65.00	0.23	1334	28.04
NBSK W15	66.35	145	3.57	3.72	841	64.20	0.24	exceeded	36.30
NBSK W15Y	66.00	138	3.54	3.72	821	63.00	0.24	exceeded	47.61
NBSK W40	67.32	183	2.82	3.40	699	51.30	0.18	exceeded	55.74
NBSK W40Y	64.88	167	2.78	3.24	664	48.70	0.19	exceeded	54.76
NBSK Y	65.50	125	4.27	4.06	866	75.70	0.27	exceeded	26.83
NBSK Y loop	67.30	122	4.74	4.12	830	66.90	0.24	2046	69.85

Green marked results indicates increased/higher properties, light orange–decreased/lower properties. NBSK (Northern bleached softwood kraft) and CMP (chemithermomechanical) indicates pulp, loop indicated that paper sheets were made in close loop sheet forming system, Y indicates samples with added yeast, W indicates grain residues filler, B indicates wheat bran filler, 15 and 40 wt% of fillers

4 Conclusions

Interest in utilizing industrial by-products for new material development has been steadily increasing to uphold environmental sustainability and enhance material circularity. From this perspective, incorporating grain and beer production by-products to partially replace raw materials in paper packaging, such as agricultural residues, appears to be a promising option provided the appropriate amount of filler based on pulp grade is selected. To explore these applications, different grain by-products (industrial wheat grain processing residues and wheat bran), along with brewer's yeast additive, were incorporated into composites with CTMP and NBSK pulp. Both wheat bran and wheat grain processing residues were added at concentrations of 15 wt% and 40 wt% to CTMP and NBSK pulps.

Testing revealed that the physical–mechanical properties of the composites generally decreased with an increase in agricultural residues fillers. However, industrial wheat grain processing residues had a less negative impact compared to wheat bran filler. On average, there was a 19.8% decrease in tensile strength, a 23.2% decrease in strain at break properties, and a 12.3% decrease in resistance to tear. The decrease was more prominent with higher concentrations of fillers.

For CTMP pulp, both types of fillers showed similar trends in impacting properties, while for NBSK pulp, wheat bran had a more pronounced effect compared to wheat grain processing residues. CTMP pulp generally exhibited lower physical–mechanical properties compared to NBSK pulp, both in control samples and those with additives.

Saccharomyces cerevisiae, or brewer's yeast, was added at a concentration of 10 wt% to both CTMP and NBSK pulps. Addition of yeast generally resulted in a decrease in physical–mechanical properties, particularly in tensile strength and tear resistance. However, yeast-containing samples exhibited greater flexibility compared to controls. The effect on barrier properties varied: while yeast increased air permeability, it also enhanced surface hydrophobicity, for example, in plain NBSK pulp produced in a closed-loop cycle, the contact angle value increased from 22° to 72° after adding yeast. Similarly, in other samples, yeast addition resulted in higher contact angle values, indicating increased hydrophobicity compared to samples without yeast. This suggests that yeast interacts with cellulose fines to enhance the material's hydrophobic properties.

Despite the decrease in properties, utilizing these by-products can contribute to sustainability by saving raw materials in paper packaging production.

These conclusions provide insights into the potential of utilizing grain by-products and *Saccharomyces cerevisiae* in paper packaging material, while also highlighting the importance of considering trade-offs between mechanical and barrier properties.

5 Future research

The presented article demonstrates that industrial wheat grain processing residues and wheat bran exhibit significant potential as additives to paper packaging material production, thereby conserving raw materials. However, the material composition and manufacturing process should be evaluated on a case-by-case basis. While *Saccharomyces cerevisiae* additive shows promise in enhancing oxygen and water barrier properties, further research on the technological integration of yeast into the paper production process is necessary.

Aerobic and anaerobic degradation tests on the tested materials will be conducted in the next stage of this research.

Author contributions All authors contributed significantly to this manuscript. Z.M. and V.V. were responsible for the original idea and the theoretical aspects of the paper; Z.M., J.L., V.L. prepared the methodology design and drafted the manuscript, Z.M. and J.L. were responsible for testing and result analysis. All authors have read and agreed to the published version of the manuscript.

Data availability The authors declare that the data supporting the findings of this study are available within the paper.

Declarations

Competing interests The authors declare no competing interests.

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