



PFAS-free molded pulp trays: effects of pulp type, refining level, and cellulose nanofibrils or biowax addition on tray performance

Jinwu Wang · Seongkyung Park ·
Colleen C. Walker

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Abstract Polyfluoroalkyl substances (PFAS) have been widely used in food packaging due to their thermal and liquid resistance; however, health and environmental concerns have driven efforts to develop safer alternatives. This study investigates the production of PFAS-free molded pulp trays using a pilot-scale fiber molding system scalable for industrial applications. The process involves vacuum-assisted fiber deposition, membrane prepress dewatering, and hot pressing. Process parameters were first optimized using a formulation of bleached hardwood kraft pulp, bio-based wax, alkyl ketene dimer, and retention aids. This commercial formulation significantly reduced water and oil absorption of the trays as compared with those without bio-wax addition. Subsequently, the effects of pulp type, refining level, and cellulose nanofibril (CNF) addition on tray properties were evaluated under the optimal set of processing

parameters, including pre-pressing (10 kN, 18 s) and hot-pressing (17 kN, 220 °C, 16 s), whereas suction time was optimized based on pulp freeness to achieve the targeted weight of trays. Softwood pulps outperformed hardwoods in mechanical and barrier properties, requiring less refining and offering a more energy-efficient path to performative molded fiber. Unbleached softwood pulp demonstrated superior performance under the tested conditions. Unrefined hardwood pulp showed the lowest performance in mechanical and barrier properties, making it the most suitable candidate for refining or reinforcement by CNFs. Preliminary energy analysis showed direct refining was more efficient than CNF reinforcement. Findings provide design and material insights for scalable, PFAS-free production of molded fiber trays.

Keywords Bleached pulp · Unbleached pulp · Hardwood kraft pulp · Softwood kraft pulp · Refining · Cellulose nanofibrils · Wet thermoforming · Dewatering · Molded fiber · Paper trays

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J. Wang (✉) · S. Park · C. C. Walker (✉)
Process Development Center, University of Maine, 5737
Jenness Hall, Orono, ME 04469, USA
e-mail: Jinwu.wang@usda.gov

C. C. Walker
e-mail: colleen.walker@maine.edu

J. Wang
Forest Products Laboratory, U.S. Forest Service, 1 Gifford
Pinchot Drive, Madison, WI 53726, USA

Introduction

Emerging molded fiber products

Cellulosic fibers and paper products offer a sustainable alternative to conventional plastics in food packaging, owing to their inherent biodegradability and

natural decomposition in soil environments. Molded fiber products have gained prominence as sustainable alternatives to plastic packaging, aligning with global initiatives to reduce environmental impact, particularly in single-use applications where recyclability and biodegradability are prioritized, including ready-meal trays, takeout containers, and frozen or refrigerated packaging. To ensure functionality, safety, and consumer acceptance, these trays must meet stringent quality requirements across mechanical, barrier, and aesthetic domains. They require appropriate mechanical performance to resist deformation during filling and handling, and to provide barriers to liquids during use, while being cost-competitive with plastic containers. However, many of these performance targets are proprietary knowledge owned by manufacturers and unpublished. Research indicates that molded fiber products exhibit varying mechanical properties, depending on the fiber composition, morphology, and processing conditions. The effectiveness of cellulose nanofibril (CNF) coatings in enhancing oil and oxygen resistance has been demonstrated in studies focusing on paperboard applications (Aulin et al. 2010); however, no cost-effective process exists for applying CNF coatings in-line on molded fiber applications. The performance of molded fiber products is governed by a complex interplay of fiber morphology, furnish composition, forming method, and post-forming consolidation. These challenges require innovations in materials, processing, tooling, and machinery.

Fiber sources of molded fiber products

Molded fiber products can be produced from a wide variety of woody and non-woody fiber sources, selected based on performance requirements, regional availability, and sustainability. In many regions, non-wood fibers such as sugarcane bagasse, wheat straw, grasses, and bamboo are utilized to reduce transportation costs and promote local resource use (Liu et al. 2023). Sugarcane bagasse, a by-product of sugar production, especially in Brazil, where over 100 million tons are generated annually, offers a sustainable feedstock. However, due to their short length, sugarcane fibers alone often yield molded products with limited mechanical strength. To address this, longer fibers, such as those from bamboo pulp, are blended with bagasse, promoting physical entanglement that

enhances the mechanical integrity of the trays (Liu et al. 2020; Zhou 2022).

Molded food trays are typically made from wood pulp, leveraging abundant forest resources and advanced wood-pulping technology. Common wood-based pulps include bleached and unbleached kraft pulp, thermomechanical pulp, and chemi-thermomechanical pulp, each offering distinct fiber lengths and bonding characteristics. Softwood kraft pulps provide long fibers that enhance strength and tear resistance, while hardwood pulps contribute to the smoothness and uniformity of the surface formation (Horn 1978; Fišerová et al. 2010). In the United States, wood pulp from the Northern Forest region, particularly hardwood species from Maine, has historically supported the paper industry (Brooks 2003; Fraver et al. 2009). Despite the impact of recent mill closures (Argul 2018), these abundant hardwood resources offer an opportunity to integrate into molded fiber applications, supporting regional economic development while advancing sustainable packaging solutions.

Currently, there are no clear guidelines for recycled fiber to be used in molded food fiber products (Semple et al. 2022). There are concerns and challenges in ensuring contaminant-free packaging products from recovered fiber (Hladíková et al. 2015). The molded pulp foodservice industry prefers using virgin fiber over recycled fiber, aiming to enhance economic viability by sourcing fiber from agricultural waste (such as bagasse and wheat straw) and fast-growing biomass, including bamboo and grass.

Fiber development for molded fiber products

Beyond fiber species selection, research has demonstrated that the strength and barrier properties, specifically water and oil resistance, of paper sheets made from pulp fibers can be significantly enhanced through refining (Lu et al. 2016). In the pulp and paper industry, two common refining methods are widely used to apply compression and shearing forces while avoiding fiber cuts: the Valley beater and the double-disk refiner. The Valley beater is typically employed in laboratory-scale studies, where pulp fibers are mechanically treated within a narrow gap between a rotating beater roll and a stationary bedplate. The refining intensity is adjusted using a weighted lever arm (Dölle and Bajrami 2021). In contrast, the double-disk refiner is standard at pilot

and industrial scales. It refines fiber suspensions by compressing and shearing fiber bundles between a rotating rotor and a stationary stator. As refining progresses through edge-to-edge, edge-to-surface, and surface-to-surface contact stages, it leads to both internal delamination and swelling as well as external fibrillation, increasing fiber flexibility and conformability, i.e., readily collapsed into a ribbon-like shape that enhances bonding development with a larger contact area within the resultant paper product (Lumiainen 2000; Nugroho 2012; Makubo 2022).

Increased the degree of refining alone, measured by the number of PFI mill revolutions, the amount of specific refining energy, or freeness, has been shown to improve both mechanical properties and barrier to air, water vapor, and oil (Lu et al. 2016). These improvements are primarily attributed to enhanced interfiber bonding due to improved fiber conformability and increased contact areas among fibers, resulting from internal and external fibrillation of cell walls (Gharehkhani et al. 2015; Upadhyay et al. 2023). The combination of refining a southern bleached hardwood kraft pulp for 16,000 revolutions and calendering a paper web, five passes at 100 °C and 7 MPa, reduced the water vapor transmission rate by 48% and achieved oil and grease resistance at the kit 9 rating (Upadhyay et al. 2023). Calendering flattens and compresses surface fibers, closes or narrows pores at the paper surface, resulting in a smooth surface and reduced air permeability, but may reduce bulk, mechanical strength, and repulpability if overdone (Upadhyay et al. 2023). Mechanically modified papers offer an alternative to laminates, multilayers, and coated materials, making them easier to recycle and more sustainable, provided liquid water resistance is not a concern. However, most products that require oil- and grease-resistance also require water resistance.

Replacing mechanical refining with CNF addition can yield comparable performance in paper and molded fiber products, offering advantages such as enhanced strength, reduced air permeability, and less fiber damage (Negro et al. 2023). For instance, a study demonstrated that adding 4.5% refined CNFs to high-yield pulp decreased air permeability by up to 68% in non-hot-pressed papers (Hu et al. 2021). When combined with hot-pressing, air permeability was further reduced by an additional 50%, attributed to increased sheet density and enhanced fiber bonding

(Hu et al. 2021). However, the potential for energy savings remains uncertain, as both pulp refining and CNF production are energy-intensive processes. Further evaluation is necessary to determine which approach is more energy-efficient in the context of industrial-scale manufacturing.

Challenges of alternative barrier treatments to PFAS

PFAS, including per- and polyfluoroalkyl compounds, have been widely used in fiber food packaging as internal (wet-end) additives due to their exceptional hydrophobic and oleophobic performance at low addition levels (Perng et al. 2012; Schaidner et al. 2017). Industrial fluorochemical sizing agents are designed to achieve grease resistance under demanding conditions, with quality control commonly involving hot-oil and hot-water holdout tests at approximately 60–100 °C for 30–60 min and, in some applications, extended oil holdout on the order of hours, depending on client specifications (Horine et al. 2021; Zhu 2024; Solenis 2025). However, PFAS are environmentally persistent and increasingly associated with adverse health effects, leading to regulatory restrictions and bans in many U.S. states and other jurisdictions (Fassler 2019; Bonato et al. 2020; Peritore et al. 2023). These regulatory developments have created an urgent need for PFAS-free barrier solutions that can deliver comparable performance while remaining recyclable, compostable, and compatible with existing molded fiber manufacturing processes. Coating is a widely used technique to impart surface barrier properties. Petroleum-based waxes and synthetic polymers, such as polyethylene and polyacrylate, have been used for this purpose; however, increasing concern over their environmental impact has spurred interest in biobased alternatives, including beeswax, soy wax, candelilla wax, and carnauba wax (Tyagi et al. 2021; Mendonça et al. 2024). Currently, there are significant technical barriers to uniformly coating 3D substrates, as standard coating equipment is designed for flat, smooth substrates. Pinholing and pooling often occur on the side wall or the bottom flat area of a 3D article if spray coating is used. In addition, molded fiber products are low-value, and their production is often fast-paced. Coating is a secondary processing step after molding, which decreases throughput, increases costs,

and reduces the competitiveness of molded fiber with plastics (Zhu 2024; Versluys 2025).

Economically, internal sizing is generally preferred due to its simplicity and integration with the existing pulp slurry preparation process. Currently, no internal sizing alternatives offer the same combination of performance and process compatibility. Additionally, compliance with compostability standards, such as the Biodegradable Products Institute (BPI) certification, presents challenges for many PFAS alternatives. One promising development is Solenis TopScreen biowax, which is reported to be both recyclable and industrially compostable, and carrying EN 13432 certification when used as a coating or wet-end additive (Jahangiri et al. 2024). However, using PFAS alternatives requires greater precision in controlling fiber morphology, slurry formulation, and forming parameters to ensure molded fiber performance. For example, to achieve 2 h of 60 °C oil holdout for a PFAS-free molded article, it is required that pulp be refined to the freeness level of 200–300 Canadian standard freeness (CSF) and 11% Topscreen bio-wax loading, thermoformed under at least 11.5 MPa pressure (Horine et al. 2021). These process parameters will greatly slow productivity.

Advances in molded fiber manufacturing

There are four typical molded pulp processes used in producing disposable food containers: one-cast, transfer molding, wet thermoforming, and dry thermoforming. Among these, wet thermoforming offers distinct advantages, including the ability to produce thin-walled edges, resulting in high shape precision and fine surface details, as well as reduced material usage and faster production cycles (Semple et al. 2022; Freville et al. 2024). The process resembles laboratory handsheet forming, in which pulp suspensions are deposited onto a wire mold under suction and subsequently dewatered, dried, and consolidated to yield molded structures (Hubbe et al. 2020; Debnath et al. 2022).

Recent technological advancements have significantly improved the precision, efficiency, and sustainability of molded pulp production. Robotic operations have been integrated into vacuum molding and demolding stages, enabling automated alignment, rapid cycle times, and improved process consistency. Tooling innovations, particularly the use of

3D-printed porous fiber mold tooling (Listek 2020) and precision wire meshes have enabled faster prototyping, enhanced surface patterning, and mold customization for intricate geometries. Notably, developments in mesh design, including optimized pore geometries and engineered multi-layer meshes, have improved vacuum efficiency, facilitated uniform pulp deposition, and enhanced water drainage during the forming stage, resulting in more consistent product thickness and reduced drying times, as well as enabling the utilization of low-quality materials that would otherwise be unusable.

Advanced systems have adopted pressurizing membranes for dewatering, such as Kiefel's silicone dewatering membrane pre-forming, to enable uniform pressure distribution, improving water removal and surface definition. In wet thermoforming, thermoforming presses serve a dual role by drying and densifying the wet fiber mats under heat and pressure. This step enhances the mechanical strength, dimensional stability, and surface smoothness of the final product, yielding well-defined molded pulp trays suitable for food contact applications. These innovations, collectively, contribute to the production of high-performance, precision-formed, and visually appealing molded pulp packaging.

Research needs and objectives

Despite the rapid expansion of the molded fiber market, scientific literature regarding the scalability of these PFAS-free interventions remains limited (Freville et al. 2024). Most existing studies focus on laboratory-scale handsheets, which fail to capture the complexities of 3D geometry and the dynamics of industrial wet thermoforming. To fully replace plastics, continued innovation is necessary, particularly in selecting fiber sources, developing fiber morphology, achieving high-precision forming, and enhancing water- and oil-resistance without compromising compostability and recyclability. Standardization is a significant challenge; clear metrics are necessary to compare molded fiber products, particularly as 3D shapes introduce complexities that flat sheets do not, such as variations in thickness, uniformity, and structural performance. Finally, scaling lab technologies to industrial production requires careful attention to material sourcing, equipment design, and process

efficiency to ensure that performance seen in small-scale trials translates reliably to mass manufacturing.

To address this gap, this study used a pilot-scale wet molding machine at the University of Maine's Process Development Center to investigate the forming of various cellulose pulps and to provide insights into the productivity and scalability of wet thermoforming for potential stakeholders. Process parameters, including pre-pressing force and duration, hot-pressing force, temperature, and dwell time, were varied to determine optimal forming conditions. Bio-based wax, alkyl ketene dimer (AKD), and retention aids were incorporated into the pulp slurry to evaluate their potential as PFAS-free alternatives for achieving substantial barrier properties in molded trays. The study investigated the impact of pulp type, degree of refining (as measured by freeness), and the addition of CNFs on tray performance. Four types of wood pulps, northern bleached hardwood kraft (NBHK), northern bleached softwood kraft (NBSK), northern unbleached softwood kraft (NUBSK), and southern bleached softwood kraft (SBSK), were tested at four refining levels. In addition, 5 wt.% and 8 wt.% CNFs were added to an NBHK pulp to assess their effect. The resulting molded trays were evaluated for physical, mechanical, and barrier properties, which were correlated with pulp type and pulp freeness to identify optimal fiber sources, refining levels, formulations, and molding parameters for high-quality trays. The outcomes of this research are expected to provide a foundation for the future development of high-performance, PFAS-free molded fiber food packaging produced via wet thermoforming.

Materials and methods

Materials

Unrefined NBHK pulp was sourced from Woodland Pulp LLC (Baileyville, ME, USA), which uses a mixed wood species comprising dominant maple, birch, beech, and poplar. Unrefined NBSK pulp was sourced from the SFK Pulp Fund commercial pulp mill in Saint-Felicien (Quebec, Canada). Unrefined SBSK pulp was obtained from a southern pine mixture. Unrefined NUBSK pulp was produced by Old Town Mill in Maine, made from a mixture of softwood species, including lodgepole pine, white

spruce, and sub-alpine fir. A bio-based wax suspension (Topscreen MF305-NA) for oil and grease resistance, a sizing agent of alkyl ketene dimer (AKD) (Topscreen MF7900-NA), and an amphoteric polyacrylamide (PAM) (Hercobond 6350), along with an anionic organic polymer (PerForm SP7242) with a three-dimensional structure (likely cross-linked polyacrylamide) for enhancing fiber retention, drainage, and uniformity in papermaking, were all obtained from Solenis (Wilmington, DE, USA). Cationic polyacrylamide (CPAM) (Percol 175), a high molecular weight and low charge density, was purchased from Ciba Specialty Chemicals (Suffolk, VA, USA). Fourier transform infrared spectroscopic analysis of the bio-based wax pointed out that it consists of a vegetable wax with a small amount of cationic starch (Zhou 2022).

Pulp refining

The pulps were refined in a 3.5 wt.% suspension using a Beloit-Jones 13-inch double-disk refiner (Beloit Corp., MA, USA). The freeness of pulp was determined using a CSF tester according to TAPPI T 227 (TAPPI 2021a). The as-received pulps were designated as coarse grades, which were refined to medium and fine grades, respectively, and the blended medium grades were obtained by mixing a coarse grade and a fine grade, each at 50% (Table 1). The gross energy consumption of refining the 586 CSF NBHK pulp to 295 CSF was recorded. It was believed that comparisons across grades would assess the effect of pulp refining levels on molded fiber trays, and comparisons within each grade would assess the effects of different pulp types. However, freeness values varied slightly within each grade, because it was very difficult to control the energy input to achieve the same freeness across different pulp types.

Bio-based wax formulation

An oil-resistant formulation consisting of 8.5 wt.% biobased wax, 1.0 wt.% AKD, 0.2 wt.% amphoteric PAM, and 0.1 wt.% anionic organic polymer, based on the oven-dry weight of the pulp, were added to a hardwood pulp blend composed of 50% 559 CSF and 50% 310 CSF NBHK pulp (NBHK B). Additives were introduced sequentially in the order listed, with 1 min of mixing after each addition and 2 min

Table 1 Pulp type, degree of refining (Canadian Standard Freeness, CSF), chemicals, and forming parameters

Pulp type	Degree of refining (CSF)	Chemical	Condition	
			Suction time (s)	Forming
NBHK B	Blend 1:1 559 + 310	435 Bio-wax formulation	1.50	Table 2
NBHK	Coarse	576 None	1.03	Pre-pressing: 18s, 10kN Hot-pressing: 16 s, 17 kN, 220 °C
	Blend C + F	445	2.50	
	Medium	386	3.43	
	Fine	295	6.25	
NBSK	Coarse	525	2.25	
	Medium	400	7.25	
	Blend C + F	388	5.60	
	Fine	250	9.50	
SBSK	Medium	468	5.25	
	Fine	350	8.85	
NUBSK	Coarse	559	2.50	
	Blend C + F	440	4.55	
	Medium	382	4.80	
	Fine	321	7.10	
CNF reinforced NBHK	NBHK B	435 0.1% CPAM (Percol 175)	2.50	
	5% CNFs	296	8.20	
	8% CNFs	213	18.5	

The suction vacuum was set at 0.07 MPa

of mixing following the final additive before article production. The sequence of chemical addition and mixing time was found to be critical to successfully achieving the desired properties. The biobased wax served as a PFAS-free alternative for oil resistance, while the AKD enhanced water barrier properties, and the retention aids improved the incorporation of the biobased wax into the fiber web.

CNF reinforced formulations

A 3.3 wt.% CNF suspension was prepared from bleached softwood kraft pulp using a double disk refiner equipped with 34-inch disks (Beloit-Jones DD 3000, Beloit Corp., MA, USA) (Bilodeau and Paradis 2018). The quality grade of the CNFs,

referred to as the fines content in this study, was determined to be 90%. The gross energy consumption, i.e., electricity consumed, was recorded. The fines content in both pulps and CNFs was determined based on the length-weighted proportion of particles shorter than 200 µm, as measured by a MorFi Fiber Analyzer (TechPap, France). This method reflects the one-dimensional nature of image analysis and is not equivalent to gravimetric methods, which define fines as particles capable of passing through a 200-mesh screen (76 µm opening) based on physical size and mass. As such, image-based and sieve-based methods capture different fractions of the fines population and may yield non-comparable values.

The effect of CNF addition on molded food trays was evaluated in this study. A reference pulp blend, consisting of 50% 559 CSF and 50% 310 CSF NBHK pulps (NBHK B), was prepared, which was identical to the blend used in the biobased wax formulation. CNFs were added to the blend at 5 or 8 wt.% based on the total cellulose solids. CPAM (Percol 175) was incorporated at 0.1% of the furnish solids as a flocculation aid in both the pulp-only and CNF-added formulations to enhance the retention of fines and CNFs within the fiber network (Table 1).

Tray characteristics

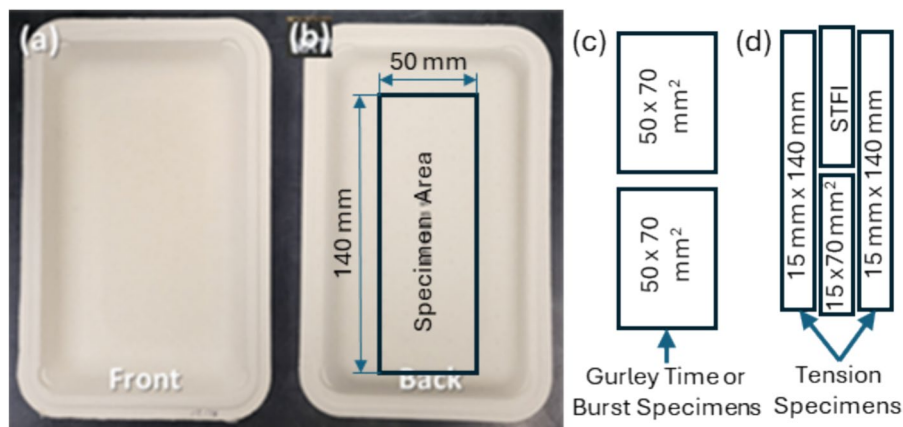
The molded fiber tray has outside dimensions of 230 mm in length, 145 mm in width, and 12 mm in depth (Fig. 1). To calculate the tray's surface area, the slightly recessed side walls were cut and flattened, resulting in a measured expanded area of 0.0337 m². This method enabled precise measurement by converting the three-dimensional recessed shape into a flat sheet. Unsized paper conditioned at 23 °C and 50% RH typically has a wet-based moisture content of around 8% (Panek et al. 2021), and sized papers stabilize toward a lower moisture content of an empirical value of 5.5%. The target weight of the tray was set to contain 17 g oven-dried pulp, which translates to 18.5 g for an unwaxed tray and 18.0 g for a waxed tray under 23 °C and RH 50 %, corresponding to a target basis weight of 531 g/m² for the waxed tray and 548 g/m² for the unwaxed tray.

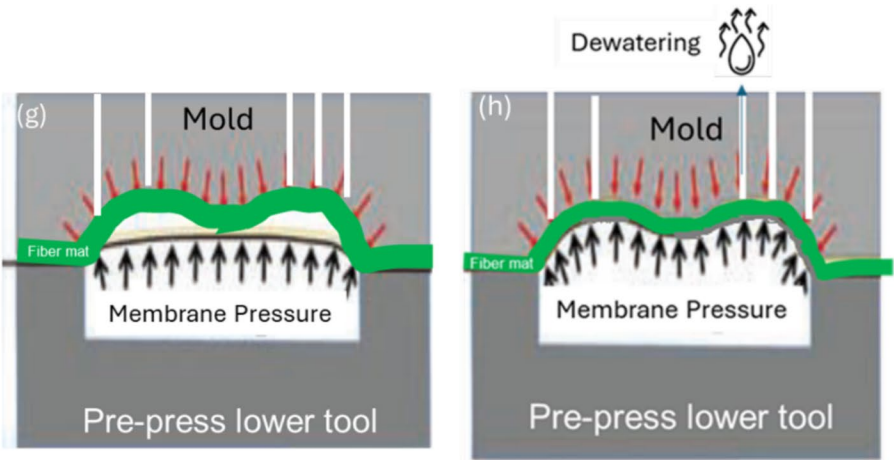
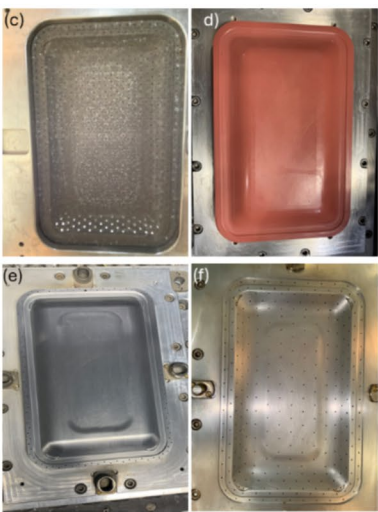
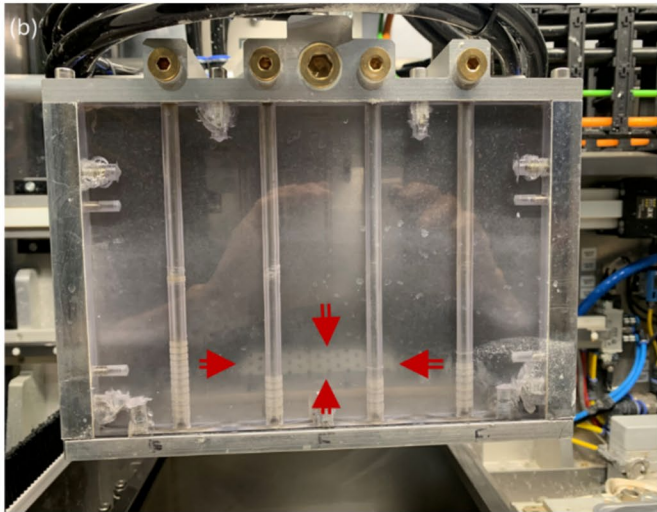
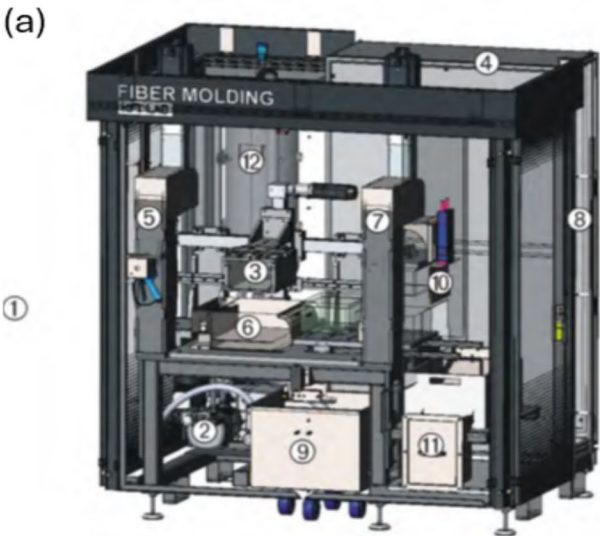
Molded fiber tray production

Molded fiber trays were produced using a pilot-scale fiber forming machine (Natureformer KFT Lab V03, Kiefel Technologies, Freilassing, Germany), as shown in Fig. 2a, including a suction tool with an installed tray mold, a pre-pressing membrane tool, and hot-pressing upper and lower tools. This machine replicates industrial-scale wet-forming processes, such as those used in Kiefel's KFT 90, with a cycle time of approximately 60 s. The process outlined in Fig. 3 comprises three key stages: vacuum forming, pre-pressing, and hot-pressing. The tool set includes a vacuum suction tool, a silicone pre-press tool, and two aluminum hot-press tools. The suction tool, a translucent housing, features a removable female tray mold (Fig. 2c) at its base, consisting of a perforated metal body and a dual-layer woven wire mesh insert (outermost mesh: 50; base mesh: 25). The mesh insert, pressed into the perforated metal body, forms a rigid mold with hierarchical water-passage channels, balancing surface smoothness (finer mesh reduces wire indents) and productivity (coarser mesh enhances drainage). The system uses compressed air to blow the tray off the tools, eliminating the need for PFAS-based releasing agents and preventing tray contamination.

All formulations were diluted to a solids content of 0.6 wt.%, using tap water, and 386 g of oven-dried feedstock was prepared for each formulation, i.e., the total weight of the suspension is approximately 64.3 kg. A pulp pump circulates slurry from the pulp container (pulp basin) to the headbox through the inlet

Fig. 1 Pictures of a molded tray made from a blend of 50% 559 CSF and 50% 310 CSF NBHK pulps with a 5 wt.% cellulose nanofibrils **a** front view and **b** back view and specimen area, **c** and **d** cutting diagram of specimens for Gurley time (porosity), bursting, tension, and short-span compression (STFI) tests of a molded fiber tray





◀**Fig. 2** **a** Kiefel KFT Lab V03 Fiber Forming Machine (1) stock preparation, (2) vacuum unit, (3) suction tool, (4) control cabinet, (5) pre-pressing station, (6) headbox, (7) hot-pressing station, (8) control panel, (9) pulp basin, (10) product pusher, (11) product unloading, and (12) gray water/vacuum vessel; **b** the suction tool housing the mold (circled by the red arrows) at the bottom side, **c** the mold, **d** the pre-pressing lower tool (silicone rubber membrane die), **e** hot-pressing aluminum low tool (male die), **f** hot-pressing aluminum upper tool (female die with moisture release hole), and **g** & **h** conceptual conformable dewatering by the silicone rubber membrane

nozzles and back to the container, maintaining a uniform fiber suspension and preventing fiber settling.

Vacuum forming: The suction tool (Fig. 2b) applies a vacuum to draw pulp slurry of ~0.6% consistency from the headbox onto the tray mold, forming a wet fiber mat. The tool submerges into the slurry, pauses at its lowest position, rises above the surface, and pauses again. During this sequence, a uniform vacuum is applied through channels in the tool's four sidewalls for a preset suction time, optimized through trials to achieve a target tray weight of 18 g/tray. Fibers are deposited onto the mold's inner surface, while water is extracted through the mesh into a vacuum vessel, which is automatically drained when the grey water level reaches a preset threshold. After vacuum dewatering, the moisture content typically ranges from 80 to 90%. The formed mat adheres to the mold and is transferred to the pre-pressing station.

Pre-pressing: At the pre-pressing station, the suction tool aligns with a flexible silicone lower tool (Fig. 2d) connected to a pneumatic system. An electric cylinder applies a preset pre-pressing force, while compressed air inflates the silicone male die to conform to the fiber mat, ensuring uniform pressure distribution and improving fiber distribution, thereby preventing lower-density zones and resulting in a uniform fiber matrix, as illustrated in Fig. 2g and h. This process, controlled for preset membrane time, expels additional water through the meshed mold openings into the vacuum vessel. The deformable silicone enhances contact, reducing moisture content to an extent controlled by applied pressure and dwell time, typically around 60%. The fiber mat remains on the suction tool and is transferred to the hot-pressing station.

Hot-pressing: The suction tool deposits the fiber mat onto a lower hot-press tool (Fig. 2e) on a shuttle table, which then positions it beneath the upper

hot-press tool (Fig. 2f). Heat (typically 150–250 °C) and pressure are applied to dry and densify the product, with both tools featuring channels connected to the vacuum system to vent evaporated water. After hot-pressing, compressed air releases the tray from the lower tool, transfers it to the upper tool, and then directs the tray to a collection box. The final moisture content is reduced to approximately 7%, achieving the desired tray properties.

CSF NBHK pulp with wax formulation

The pre-pressing (force and time) and hot-pressing (force, temperature, and time) parameters can be precisely adjusted (KFT Lab Manual, Kiefel GmbH). Table 2 presents 15 wet thermoforming process conditions used for the bio-based wax formulation to explore different operational settings with the 435 CSF NBHK pulp, which was a blend of 559/310 CSF NBHK pulp. Pre-pressing forces of 0, 6, and 10 kN were applied for either 15 or 18 s, while hot-pressing forces of 13 and 17 kN were applied at temperatures of 200, 220, or 240 °C for either 16 or 19 s. Two trials were conducted at different times, and each produced eight trays under each set of conditions, resulting in 120 trays per trial and 240 trays across the two trials.

The performance of the molded fiber trays produced under these conditions was evaluated based on tensile index, tensile energy absorption (TEA), burst index, bulk, oil absorbency, and water absorbency. The basis weight was calculated as the tray weight divided by its expanded area. The average of the 16 trays is the basis weight for each set of conditions, as reported in Table 2. For each set of conditions, two trays (one from each trial) were sampled to evaluate water- and oil-barrier properties, respectively. Absorbency was the average of two trays.

Four trays from each condition (two per trial) were sampled for thickness and burst index. Six thickness measurements were taken on each tray. The bulk of each tray was calculated by the average thickness of the 6 points divided by the basis weight. The average of the four trays was the bulk for each set of conditions. Two 50 mm × 70 mm specimens were cut from the flat bottom area of each tray and tested for burst index, with two specimens placed inner side up and two placed outer side up. The burst index for each condition set was the average of eight specimens. Four trays (two from

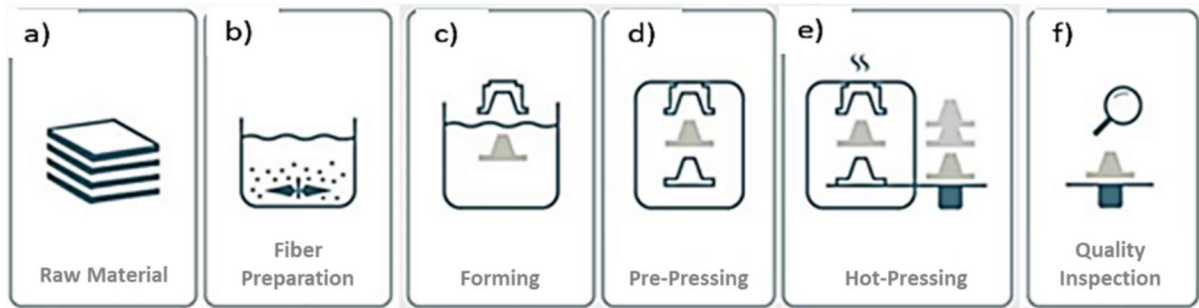


Fig. 3 a–f Steps of producing a 3D molded fiber product, such as a shallow tray, with a Kiefer Fiber Forming Machine

Table 2 Forming parameters and corresponding tray performance for the 435 CSF NBHK pulp with bio-based wax addition (see standard deviations in Supplementary Table S1)

	Pre-, hot-pressing conditions ^a	Basis weight (g/m ²)	Tensile index (N/mg)	Tensile strain (%)	TEA ^b (J/m ²)	Burst index (kPa m ² /g)	Bulk (cm ³ /g)	Oil absorption (wt.%) ^c	Water absorption (wt.%) ^d
1	15/6k-16/13k/220	534.3	13.74	1.33	60.2	0.56	1.72	29.1	9.9
2	15/6k-16/17k/240	530.1	14.11	1.28	58.9	0.58	1.65	25.1	9.6
3	15/10k-19/13k/220	536.0	14.24	1.37	64.6	0.53	1.71	26.2	9.5
4	15/10k-19/17k/240	543.6	14.64	1.34	65.1	0.61	1.64	22.8	9.5
5	18/6k-19/17k/220	531.7	14.98	1.43	69.9	0.55	1.64	24.4	10.5
6	18/6k-19/13k/240	531.8	13.88	1.34	61.8	0.56	1.75	26.7	9.2
7	18/10k-16/17k/220	530.7	15.36	1.50	74.0	0.62	1.61	24.6	10.2
8	18/10k-16/13k/240	542.3	14.56	1.39	68.7	0.58	1.72	26.3	9.9
9	15/6k-16/17k/220	533.1	14.38	1.35	63.0	0.59	1.62	24.1	10.3
10	18/0k-16/17k/240	533.8	13.77	1.33	58.4	0.55	1.64	20.7	9.3
11	18/10k-16/17k/240	536.7	15.28	1.50	74.9	0.60	1.62	24.1	10.2
12	18/0k-16/17k/220	536.3	13.46	1.30	56.5	0.54	1.64	20.6	9.0
13	18/10k-16/17k/200	534.6	14.67	1.45	68.4	0.58	1.60	24.0	12.3
14	15/6k-16/17k/200	528.6	14.48	1.40	65.3	0.61	1.60	23.7	12.0
15	18/0k-16/17k/200	531.8	13.60	1.34	57.8	0.54	1.61	19.3	9.0
Average		534.4	14.4	1.38	64.5	0.57	1.65	24.1	10.0
COV (%)		0.8	4.2	4.88	8.9	5.0	3.0	10.6	9.8
435 CSF NBHK w/o wax		518.3	20.7	1.71	116.7	0.93	1.7	49.2 ^e	110.4 ^f
Increase over w/ wax (%)		− 3.1	30.8	19.5	44.7	38.2	2.9	–	–

^aThe forming parameters are listed in the order of pre-pressing time/force/hot-pressing time/force/ temperature; ^bTEA: tensile energy absorption; ^cOil Absorption @60 °C for 30 min; ^dWater Absorption @ 75 °C for 30 min; ^eOil Absorption @60 °C for 2 min. wt.%; ^fWater Absorption @ 75 °C for 2 min. wt.%

each trial) were sampled. Three specimens measuring 15 mm × 140 mm were cut from the bottom flat area of each tray and tested for tensile strength. The tensile index, strain at break, and TEA were calculated as the average across 12 specimens for each set of forming conditions.

Pulps without wax

Molded fiber trays were produced by wet thermoforming using pulps that varied in type, refining level (freeness), and CNF addition, as detailed in Table 1. Based on performance results from the bio-based wax formulation, thermoforming conditions

were standardized to a pre-pressing time of 18 s at 10 kN, followed by hot-pressing at 220 °C for 16 s at 17 kN. Suction time was found to be a critical parameter, increasing with decreasing pulp freeness and increased CNF content, to achieve the target tray weight and facilitate water removal (Table 1).

More than 20 trays were produced for each of the 17 freeness levels across five pulp types, resulting in over 340 trays. For each freeness level, four molded trays were selected for physical property evaluation, yielding a total of 68 samples. Basis weight was calculated by dividing the average weight of the four trays by the expanded surface area (0.0337 m²). Tray thickness was measured at two locations (left and right) on each tray, yielding a total of 8 measurements per freeness level. Bulk (specific volume) was determined by dividing the average thickness by the corresponding basis weight.

For mechanical testing, four flat rectangular specimens (140 mm×50 mm) were cut from the bottom surfaces of the four trays (Fig. 1). Each rectangular specimen was cut into three strips (140 mm×15 mm), yielding 12 test specimens. Eight specimens (two from each side) were used for tension testing to measure tensile index, tensile strain, and TEA, while the remaining four center strips were halved to produce eight specimens for short-span compression testing. Tensile properties were evaluated using a universal testing machine (Instron 5564, Norwood, MA, USA) in accordance with TAPPI T 494 (TAPPI 2022a). The short-span compression index was measured using an L&W STFI tester (Lorentzen & Wettre, Kista, Sweden) in accordance with TAPPI T 826 (TAPPI 2021b).

An additional set of four trays per freeness level was sampled for air resistance testing. Two specimens (50 mm×50 mm) were cut from the bottom flat area of each tray, for a total of eight specimens per freeness level. Air resistance was measured using a Gurley densometer (Gurley Precision Instruments, NY, USA) in accordance with TAPPI T 460 om-16 (TAPPI 2016). Finally, four more trays were sampled at each freeness level: two for water absorbency and two for oil absorbency.

Characterization of molded fiber trays

All molded fiber trays were conditioned at 23 °C and 50% relative humidity for 24 h prior to testing.

Figure 1 shows the cutting diagram for specimens. The average properties are presented in Tables 2 and 3.

Water and oil absorption: The Cobb test (TAPPI T 441) and Kit test (TAPPI T 559) are standard methods in pulp and paper research for assessing water and oil resistance for sheet materials. For products made with non-PFAS grease/oil-resistant additives, a Harmonized Hot Oil Test standard for foodservice products (FPI 2013) was used. Since the tray is a container, liquids are directly placed into it without using a Cobb ring clamp. There must be no observed oil penetration stains on the bottom surface; then, it proceeds to calculate liquid absorbency.

Specifically, 50 mL of tap water and Mazola corn oil (ACH Food Companies, Inc., Oakbrook Terrace, Illinois, USA) were used to test resistance to water and oil, respectively. For trays treated with the biobased wax, oil absorption was assessed at 60 °C for 30 min, and water absorption was evaluated at 75 °C for 30 min. For trays without wax treatment (treated only with refining or CNF addition), a shorter contact time of 2 min was used, as these trays absorbed liquid rapidly, often leading to penetration, deformation, or collapse. This shorter exposure yielded more manageable, differentiable test results. In contrast, the biobased wax-treated trays retained structural integrity for longer exposure times.

Absorption was calculated based on the mass difference before and after liquid exposure, normalized to the initial conditioned mass at 23 °C and 50% relative humidity. Trays that collapsed due to water saturation were graded as failures in water resistance. Similarly, trays were considered to have failed the oil resistance test if oil penetrated through and wetted the tester's hand. Only trays that showed no oil penetration were evaluated further.

Mechanical testing: The tension was conducted using a universal testing machine (Instron 5564, Norwood, MA, USA) in accordance with TAPPI T 494 (TAPPI 2022a), with a gauge length of 100 mm and a sample size of 15 mm×140 mm. The short-span compression index was measured using an L&W STFI tester (Lorentzen & Wettre, Kista, Sweden), following TAPPI T 826 (TAPPI 2021b), with a 15 mm-wide specimen and a test gap of 0.7 mm. The burst index was assessed using a L&W bursting strength tester (Lorentzen & Wettre, Kista, Sweden) in accordance with TAPPI T 403 (TAPPI 2022b). The test

Table 3 Average properties of trays without bio-wax addition (see Supplementary Table S2 for standard deviations)

Pulp type	CSF (mL)	Basis weight (g/m ²)	Caliper (mm)	Bulk (cm ³ /g)	Tensile index (N m/g)	Tensile Strain (%)	TEA (J/m ²)	Burst index (kPa m ² /g)	STFI (N m/g)	Porosity (Gurley s)	Oil absorption (%)
NBHK	576	548.8	0.874	1.59	9.7	0.97	32.1	0.48	22.9	18.4	52.6
	386	548.3	0.920	1.68	21.7	2.29	175.1	1.12	30.3	52.4	43.6
	295	547.5	0.942	1.72	25.1	2.58	231.8	1.14	32.7	75.5	40.9
	445	549.9	0.900	1.64	18.4	1.80	115.8	0.80	31.3	40.3	46.3
NBSK	525	543.7	0.926	1.70	24.6	2.29	219.7	2.12	29.7	36.1	42.7
	400	539.9	0.913	1.69	24.6	2.65	261.0	2.18	37.2	79.9	33.0
	250	499.2	0.845	1.69	25.0	3.34	332.9	2.21	40.6	87.1	32.7
	388	552.6	0.963	1.74	24.7	3.54	388.5	2.07	29.0	57.1	38.0
SBSK	468	527.2	0.894	1.70	26.0	3.09	288.9	1.83	28.6	48.4	34.2
	350	529.8	0.905	1.71	28.3	2.79	277.2	2.22	32.0	79.6	34.5
NUBSK	559	547.5	0.887	1.62	27.5	2.73	259.6	2.05	31.5	77.6	35.5
	382	546.9	0.928	1.70	28.9	2.70	267.2	2.01	34.2	114.8	31.1
	321	529.0	0.882	1.67	30.4	2.57	253.2	1.88	31.7	125.8	28.6
	440	547.6	0.906	1.66	29.5	2.79	281.8	2.13	36.8	105.7	31.3
NBHK B	435	518.3	0.85	1.64	20.7	1.71	116.7	0.93	30.2	31.1	49.2
5% CNF	296	522.9	0.89	1.70	26.4	2.36	215.7	1.33	32.4	70.5	43.2
8% CNF	213	476.4	0.81	1.70	30.8	2.73	280.4	1.60	33.1	115.5	43.4

CSF: Canadian Standard Freeness; TEA: tensile energy absorption; STFI: short-span compression index; Oil absorption @60 °C for 2 min

utilized a circular diaphragm that applied pressure until the paper burst. The specimen was clamped between two annular plates with a circular opening, around 30 mm (1.2 inches) in diameter.

Statistical analysis

Statistical analyses were performed using Microsoft Excel. One-way ANOVA was used to assess differences among multiple groups, and post hoc comparisons were conducted using the Tukey–Kramer Honestly Significant Difference (HSD) test, implemented in Excel's Data Analysis Toolpak. For comparisons between two groups, the Student's *t*-test was applied. Different alphabetical letters in the graphs indicate statistically significant differences among groups. A *p*-value of less than 0.05 was considered statistically significant.

Results and discussion

Effects of processing parameters on bio-based waxed trays

This study investigated the impact of key processing parameters, pre-pressing force and time, as well as hot-pressing force, temperature, and time, on the critical material properties of molded fiber trays, including tensile index, strain at break, TEA, burst index, bulk, oil uptake, and water uptake, as shown in Table 2. Standard deviations for all values are provided in Supplementary Table S1. The results were normalized to the minimum value for each property, yielding values of 1–1.5 across all properties, allowing them to be plotted on a single graph for each processing parameter and reducing the number of plots. For each processing variable, normalized property values at different levels were averaged and plotted to observe the trends shown in Fig. 4. Generally, the optimal targets for packaging paper are to increase mechanical and barrier properties while maintaining bulkiness. Higher tensile index, TEA (integration of strength and deformation information), burst index, and bulk values indicate better physical performance, while lower oil and water uptake reflect improved barrier properties. In this analysis, a process condition was considered optimal when three or more properties showed favorable outcomes.

As shown in Fig. 4a, eliminating pre-pressing (0 kN) reduced oil and water uptake but resulted in significantly lower bulk, TEA, tensile, and burst indices. These findings suggest that while no pre-pressing and hence higher moisture content under hot pressing might reduce local fiber porosity and bulkiness (thus improving barrier performance), it compromises fiber bonding and mechanical strength globally. Increasing the pre-pressing force to 6 and 10 kN improved mechanical properties, likely due to enhanced fiber consolidation and hydrogen bonding, though it slightly reduced barrier performance.

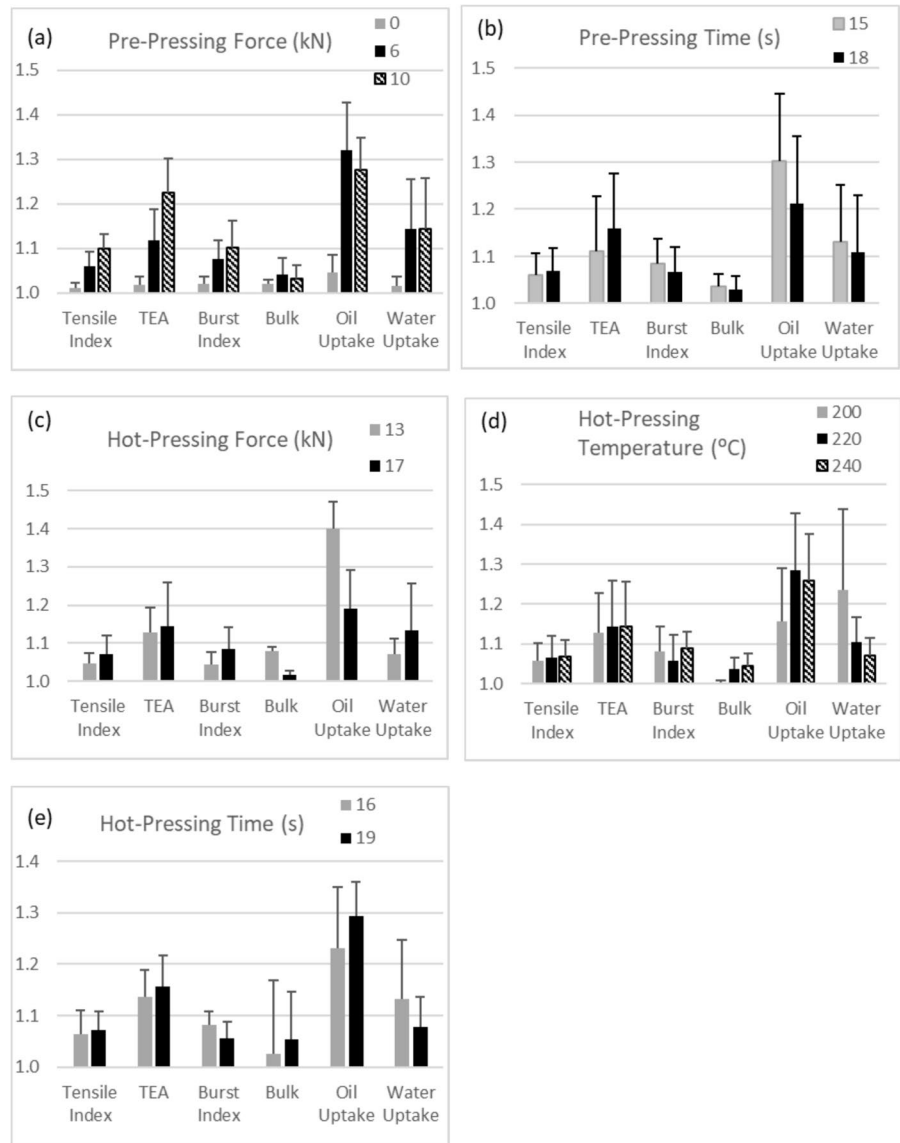
Figure 4b indicates that extending the pre-pressing time from 15 to 18 s reduces both oil and water uptake and increases TEA, while maintaining comparable tensile index, burst index, and bulk. This suggests that prolonged pre-pressing time may allow more uniform moisture removal and fiber mat stabilization, improving barrier properties without compromising strength. Based on these results, a pre-pressing condition of 10 kN for 18 s was deemed favorable.

As shown in Fig. 4c, increasing the hot-pressing force from 13 to 17 kN improved the tensile index, TEA, and burst index, and notably reduced oil uptake, demonstrating the beneficial effects of higher pressure during hot pressing. Figure 4d shows that a hot-pressing temperature of 240 °C yielded the lowest water uptake, as well as the highest burst index and bulk, although it had only a moderate effect on the tensile index and TEA. Similarly, Fig. 4e shows that increasing the hot-pressing time from 16 to 19 s had a mixing effect, improving water barrier properties, tensile index, TEA, and bulk, but decreasing oil barrier and burst strength.

Despite these improvements, it was observed that applying the highest temperature (240 °C) and the longest pressing time (19 s) occasionally caused surface defects, such as blistering. It was noted that the target production parameters for molded fiber were a short cycle time and low pressure to improve process efficiency without substantially compromising product performance. Therefore, to balance process efficiency and product performance and appearance, hot-pressing conditions of 17 kN force, 220 °C temperature, and 16 s time were selected for subsequent tray production.

In summary, we screened a set of processing parameters for reasonable product performance, including a pre-pressing force of 10 kN for 18 s and a

Fig. 4 Comparison of relative properties at different process parameters; each property was normalized relative to its minimum (as the unity) and was averaged at a specified process parameter, as labeled in titles and legends. The error bar is the standard deviation of the normalized data



hot-pressing force of 17 kN for 16 s at 220 °C, which were used in subsequent experiments to explore the effects of pulp type and degree of refining.

Effect of fines content on wood pulp freeness

In this study, the fiber length and fines contents were evaluated using a MorFi Fiber Analyzer (TechPap, France) for some pulps. The fiber lengths of 576, 445, 386, and 295 CSF northern hardwood kraft pulps were measured at 0.85, 0.79, 0.803, and 0.788 mm, respectively. The fiber lengths of the 559, 440, 382, and 321 CSF NUBSK pulps, as well

as of the 350 CSF SBSK pulp, were measured at 1.91, 1.93, 1.90, 1.87, and 1.69 mm, respectively. Figure 5 shows the relationship between the fines content and wood pulp freeness. Generally, increasing the refining level shortens fibers and increases fines content, thereby decreasing freeness. The unbleached pulp achieved a similar freeness with less fines content, indicating that it drains more poorly for a given fines content, potentially due to lignin and other extractives. The retardation of water draining after CNF addition is likely attributable to increased fines content. The CNF addition

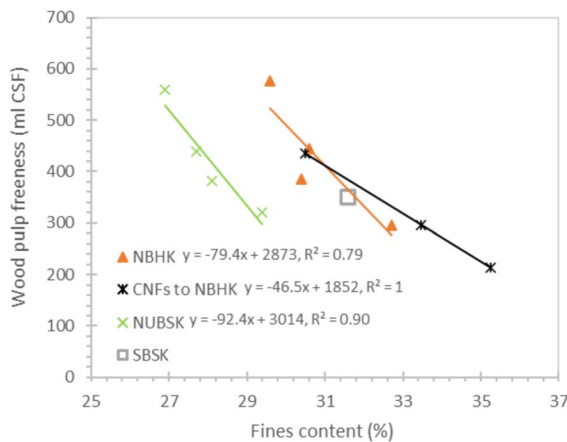


Fig. 5 The effect of fines content on wood pulp freeness

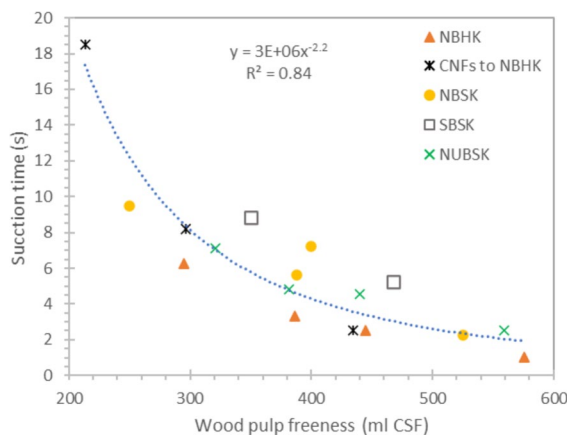


Fig. 6 The required effective suction time increases roughly proportionally to the square of the decrease in pulp freeness

decreased pulp freeness at a lower rate than refining, indicating better dewatering with CNFs.

Effect of freeness on suction time

The tray weight indicates the mass of fibers collected from the slurry by vacuum suction during the forming stage, which is determined by the vacuum pressure and suction time. Generally, the vacuum pressure was maintained at a constant level during the runs; the suction time was adjusted through trial and error based on the slurry characteristics to achieve a specific weight of 18 g in this study. Figure 6 shows that the required effective suction time

increases approximately as a power function of two with decreasing pulp freeness (i.e., increasing pulp fineness). This slower formation can be attributed to lower water drainage, due to decreased fiber length and increased fines content as the fibrillation levels increased. The shortened fibers and increased fines in the feedstocks increased the likelihood of clogging drainage paths, known as sheet sealing, slowing the removal of water from the pulp slurries. A high water-binding capacity of fines, combined with their high surface area, can increase the suction time during wet thermoforming (Hubbe et al. 2020; Debnath et al. 2022). This typically increased the cycle time of molding a tray, decreasing productivity.

Figure 6 indicates that the bleached softwood pulps required slightly longer suction times at similar freeness levels to achieve a similar basis weight. This indicates that softwood and hardwood pulps behave slightly differently during vacuum-formation drainage compared to gravity drainage, as observed during the CSF test. Drainage behavior tested under gravity may differ from that tested under vacuum. A similar weight of the molded tray can be achieved by extending the suction time. If higher-refined or softwood pulps may require less mass to achieve similar performance, a slightly reduced suction time can be implemented.

Physical properties of molded fiber trays without bio-wax

This study did not investigate the formation of the tray, i.e., how the total mass was distributed among the tray's rim, wall, and bottom, but rather focused on the tray's weight and a nominal basis weight. The basis weight of a molded tray was calculated by dividing its total weight by its nominal expanded area. Table 3 summarizes the average results, and Standard deviations for all values are provided in Supplementary Tables S2. Table 4 shows global variations in properties across all trays due to pulp type, freeness level, and suction time. Basis weight was mainly controlled by effective suction time. Although the suction time was set up to achieve a constant basis weight, a 3.9% coefficient of variation and a 16% change from the minimum to maximum basis weight remain. However, the coefficient of variation was reduced to 2.3% for bulk, indicating it was less influenced by pulp type and process

Table 4 Property variations among pulp type, freeness level, and suction time

	Basis weight (g/m ²)	Thickness (mm)	Bulk (cm ³ /g)	Tensile index (N m/g)	Tensile strain (%)	Tensile energy (J/m ²)	Short-span compression (N m/g)	Porosity (Gurley s)	Oil absorption 60 °C, 2 min (%)
Minimum	476.4	0.8	1.6	9.7	1.0	32.1	22.9	18.4	28.6
Maximum	552.6	1.0	1.7	30.8	3.5	388.5	40.6	125.8	52.6
Change %	16.0	18.9	9.4	216.1	267.2	1110.9	76.9	584.0	84.2
Average	533.9	0.9	1.7	24.9	2.5	235.2	32.0	71.5	38.9
CV (%)	3.9	4.2	2.3	20.7	24.4	36.6	12.2	44.4	18.0

parameters. The CVs of other properties exceed the basis weight CV, amplifying the variation in basis weight. This indicates that, aside from basis weight, factors such as pulp type and fineness also influence the results. The sensitivity to these factors, in order from highest to lowest, is oil absorption, porosity, TEA, tensile strain, tensile index, and short-span compression index. Mechanical properties and barrier properties are specifically discussed in the following sections.

Figure 7a shows that basis weight (g/m²) generally increases with pulp freeness (coarser pulp) across most pulp types, except for NBHK pulps, which maintain a consistent basis weight regardless of freeness. The lower basis weights observed at lower freeness levels (more refined pulp) suggest reduced pulp pickup during tray formation. Suction time, which varied by pulp type, was longer for finer and softwood pulps. For NBHK, NBSK, and NUBSK pulps at higher freeness levels, suction times were appropriately calibrated to achieve consistent basis weights. In contrast, inadequate suction times for other pulps or lower freeness levels led to inconsistent tray weights. These results highlight the need to adjust suction time based on pulp type and freeness to ensure consistent basis weight across different pulps during forming.

Figure 7b illustrates the bulk (cm³/g) of molded trays, which is the inverse of the apparent density and reflects the volume per unit mass. Bulk generally increases with decreasing freeness (higher fineness) for most pulp types, except bleached softwood pulps, which show no significant variation. Coarser softwood pulps produce slightly bulkier trays than hardwood or unbleached pulps, but bulk values converge towards lower freeness across pulp

type, indicating that refining minimizes fiber-type differences.

Figure 7c illustrates the thickness (mm) of molded trays across varying levels of freeness. As thickness equals basis weight multiplied by bulk, and bulk variations are minimal, thickness trends closely align with those of basis weight, showing similar but less pronounced changes with freeness.

Dewatering and consolidation

A wet mat contains moisture in the pores between fibers, fiber lumens, and microscopic cell wall pores. A significant amount of water must be removed not only from between fibers but also from within fiber lumens and pores prior to thermoforming to prevent blistering. Dewatering during molded fiber tray production occurs in sequential stages: vacuum-assisted forming followed by mechanical pre-pressing. Water is preferentially pressed out from larger pores; there is a lower limit of pore size under a specific pressure from which water can be mechanically pressed out. High fines content or highly refined fibers retain more water and leave higher residual moisture, which can hinder the effectiveness of hot pressing.

It is questionable whether the conventional dewatering index of freeness is a reliable indicator of vacuum forming and pre-pressing. CSF, measured under gravitational flow, primarily reflects how readily water drains through interfiber pores larger than approximately 100 µm, as estimated by the Young–Laplace equation. However, CSF does not adequately reflect water-removal performance under vacuum or mechanical pressure. Vacuum levels around 0.07 MPa and mechanical pressures exceeding 0.2 MPa apply significantly higher driving forces,

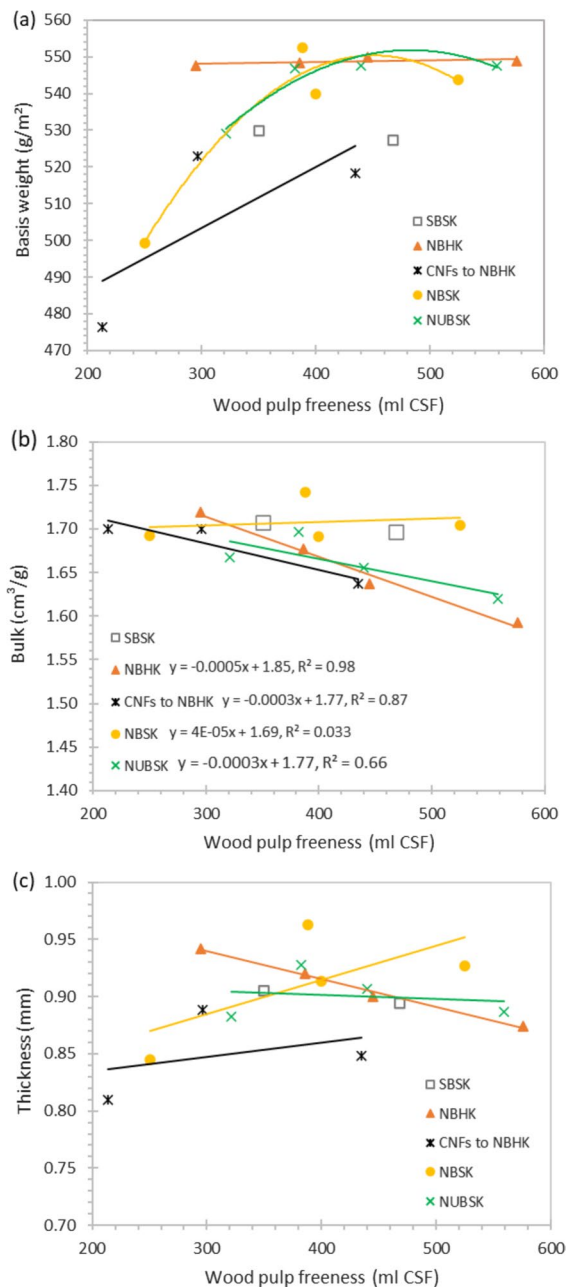


Fig. 7 The basis weight (a), bulk (b), and thickness (c) of trays vary with pulp freeness

enabling water extraction from finer pore structures and partially collapsed lumens, components that are less responsive under gravity alone. These dewatering processes promote viscous water flow, but their efficiency is constrained by capillary forces; water in pores smaller than $\sim 1\text{--}2\text{ }\mu\text{m}$ remains trapped even

under pressure. Thus, while freeness offers a useful baseline for characterizing pulp drainage, it cannot fully predict pulp behavior under the vacuum and pressure conditions typical of molded fiber forming. This analysis explains why pulps with similar freeness levels required different suction times, leading to trays that performed differently. It reports that water retention values under centrifugal forces correlate well with freeness, which is not appropriate for measuring vacuum and pressure-based dewatering behavior (Botha 2015).

Kerekes and McDonald (2020) noted that chemical pulping and refining increase the volume of fine pores within the wet network of fibers, which enhances their water-holding capability and results in a higher water content of the wet tray prior to hot-pressing. In addition, fines had a high probability of clogging screen openings, reducing water drainage. This elevated water content, combined with the relatively low pressure and short duration of the hot-pressing stage, limits water removal, fiber contact, and hydrogen bond development, resulting in a higher specific volume or bulk after pressing. Moreover, bleached softwood pulps exhibit greater water-holding capacity under comparable dewatering conditions (Kerekes and McDonald 2020) and flexibility of plugging screen openings, contributing to their relatively high bulk values (Fig. 8b). This is different from the observations for handsheets with a low grammage, which generally exhibit a trend of decreasing bulk with decreasing freeness (Makubo 2022).

Mechanical properties of molded food trays

The tensile index (N m/g) measures the maximum tensile force per unit width, normalized by basis weight, indicating the material's strength relative to its mass, similar to specific strength, which is calculated by normalizing strength by density. Higher values mean stronger material for its weight. As shown in Fig. 8a and Table 4, the minimum tensile index is 9.7 N m/g for the 576 CSF NBHK pulp, with a maximum of 30.8 N m/g for the 8% CNF added to the 435 CSF NBHK pulp, representing a 216.1% increase.

The tensile index of hardwood pulp-based trays scales linearly with pulp freeness, with R^2 values approaching unity for both NBHK and CNF-added pulps. Adding CNFs to hardwood pulp decreased its freeness, producing effects like refining. The

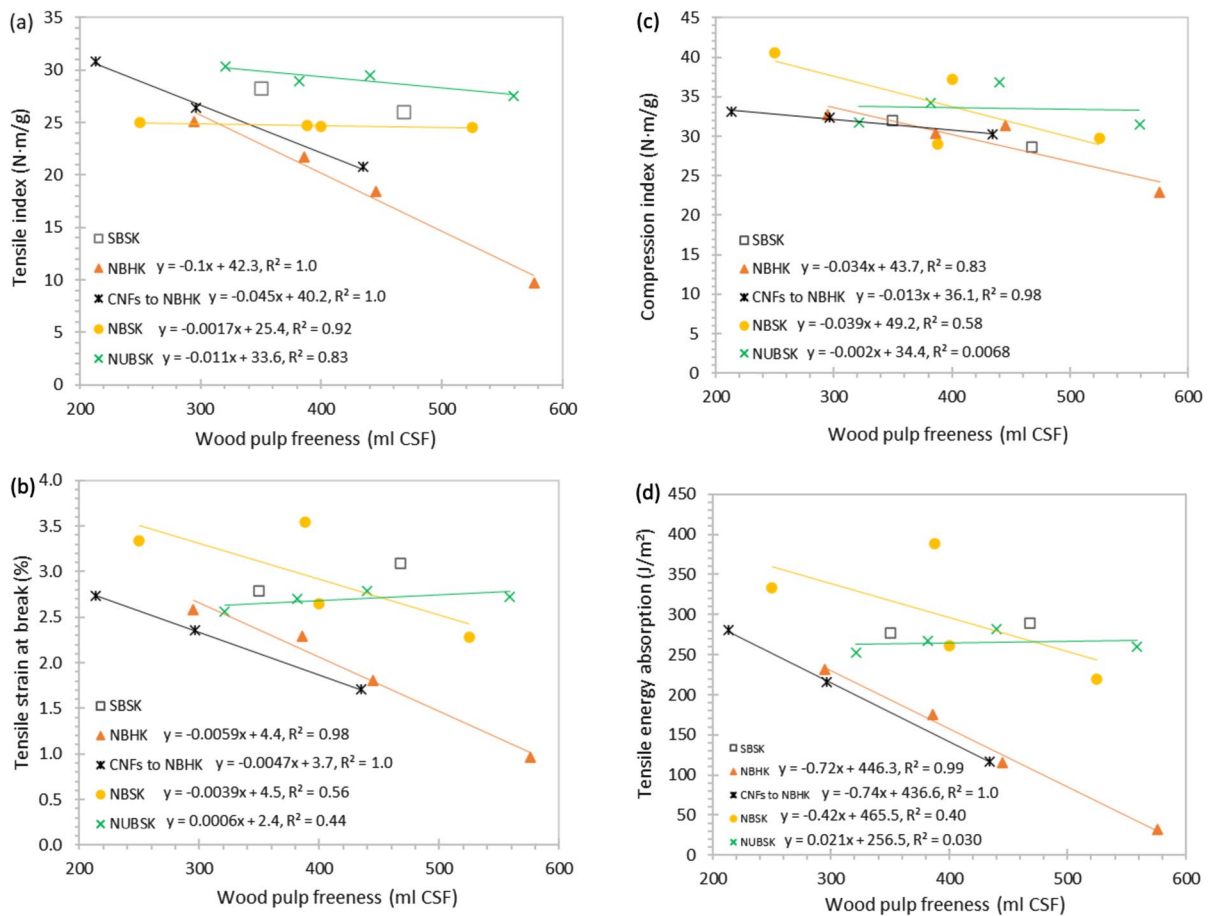


Fig. 8 Mechanical properties of the molded tray change with pulp freeness: **a** tensile index, **b** tensile strain at break, **c** short-span compression index, and **d** tensile energy absorption

unbleached northern softwood pulps provided the highest tensile index across all freeness levels, with a slight effect of freeness change. Softwood pulps have higher tensile indices than hardwood pulps, especially at higher freeness levels. However, refining hardwood pulps was more effective at increasing tensile indices than refining softwood pulps, which maintained similar tensile indices across different freeness levels.

Yokoyama et al. (2009) reported tensile indices for a copy paper at 65.6 N m/g (MD) and 29.6 N m/g (CD), an unbleached kraft paper at 75.0 N m/g (MD) and 42.4 N m/g (CD), and a newsprint at 57.1 N m/g (MD) and 13.6 N m/g (CD). These reflect paper network properties, including fiber strength, bonding, and orientation. Fibers in molded trays are generally randomly distributed, and the tensile index should be averaged across all directions. Their tensile indices

are significantly lower than those of machine-made papers in the machine direction and at the same order of magnitude in the cross direction, as reported by Yokoyama et al. The absence of strength additives in the formulations of the molded trays, as well as the constrained dewatering and hot-pressing process, may explain their lower tensile indices. However, the tray tensile indices are larger than those of sugarcane fiber trays ranging from 2.4 to 11.2 N m/g (Ngiwngam et al. 2023).

Tensile strain at break (%) is the percentage elongation at break, indicating a material's stretchability and flexibility. Higher values indicate more elastic or flexible material. As shown in Fig. 8b and Table 4, the minimum tensile strain is 1.0% for the 576 CSF NBHK pulp, with a maximum of 3.5% for the 388 CSF NBSK pulp, representing a 267.2%

increase. Softwood pulps generally provided molded trays with higher tensile strain at break than hardwood pulps. Refining or adding CNFs increased tensile strain, except for NUBSK pulp, which showed a slight decrease. These levels of deformation for softwood pulps are smaller than those reported for Nordic bleached softwood kraft handsheets, ranging from 4.4 to 5.5%, but at the same order of magnitude for hardwood pulps as those of chemi-thermomechanical hardwood handsheets, ranging from 0.8 to 1.8% (Korpela et al. 2021).

The short-span compression index of paperboard measures its compressive strength over a very short span, normalized by its grammage. It is commonly used to evaluate the edgewise compression strength of paper and board materials. As shown in Fig. 8c and Table 4, the minimum short-span compression index is 22.9 N m/g for the 576 CSF NBHK pulp, with a maximum of 40.6 N m/g for the 250 CSF NBSK pulp, representing an increase of 76.9%. The short-span compression index slightly increases with fineness, and its values are closer to those of other mechanical properties, indicating that this property is less influenced by pulp type and fineness than other properties. Frank reported that 300 linerboards with grammages ranging from 150 to 440 g/m² have a short-span compression index around 18 N m/g (Frank 2003). Popil reported that 12 linerboards and 5 mediums have short-span compression indices ranging from 17 to 26 N m/g. Therefore, the molded trays have superior short-span compression strength to most containerboards. This is understandable, since containerboards are often made largely from recycled fibers from old corrugated containers, which are typically damaged, compared with the virgin fibers used in this investigation.

Tensile energy absorption (J/m²) represents the energy absorbed per unit area of the sheet along its in-plane dimensions under tension and is calculated by integrating the force–displacement curve, then divided by the product of the sample width and gauge distance, which represents energy absorbed per unit of the material's surface area. Higher values mean better durability and impact resistance. As shown in Fig. 8d and Table 4, the minimum tensile energy absorption is 32.1 J/m² for the 576 CSF NBHK pulp, with a maximum of 388.5 J/m² for the 388 CSF NBSK pulp, representing an increase of 1110.9%. Like the tensile index and strain, softwood pulps

generally provided molded trays with higher tensile energy absorption than hardwood pulps. Refining or adding CNFs increased this absorption, except for NUBSK pulp, which showed a slight decrease.

Tensile energy absorption is not an intrinsic material property; rather, it depends on the thickness of the test paper. The larger the thickness, the larger the tensile energy absorption. Specific tensile energy absorption is obtained by dividing tensile energy absorption by thickness, indicating a material's intrinsic toughness. Their values for the molded trays are in the range of 0.0367 to 0.4031 MJ/m³ as shown in Fig. 9a. Yokoyama et al. (2009) reported specific tensile energy absorption for a copy paper at 0.45 MJ/m³ (MD) and 0.86 MJ/m³ (CD), an unbleached kraft paper at 0.53 MJ/m³ (MD) and 0.84 MJ/m³ (CD), and a newsprint at 0.19 MJ/m³ (MD) and 0.19 MJ/m³ (CD). Therefore, the toughness of the molded trays is

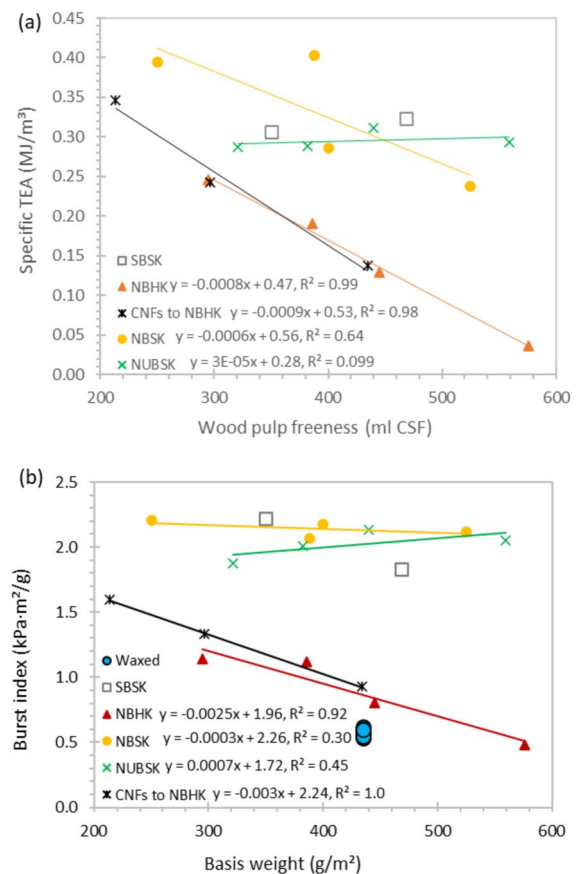


Fig. 9 Specific TEA (tensile energy absorption) (a) and burst index (b) changes with wood pulp freeness

inferior to that reported in the literature, suggesting that it can be further improved by adding additives, refining, or adjusting process parameters.

Figure 9b shows the burst index of molded fiber trays as a function of pulp freeness for different wood pulp types. Trays produced from NBHK pulps exhibit a clear negative correlation between burst index and freeness ($R^2=0.92$), indicating that increased coarseness (higher freeness) leads to reduced burst strength, likely due to diminished bonding areas between fibers. The addition of CNFs decreases freeness and increases burst strength, but it does not raise it to a level compatible with softwood pulps. In contrast, NBSK and NUBSK pulps maintain consistently higher burst indices across a range of freeness values, with minimal sensitivity to refining levels ($R^2=0.30$ and 0.45 , respectively); similarly, the SBSK pulp exhibits this characteristic. This suggests that the inherent fiber length and bonding potential of softwoods contribute to greater mechanical strength, even at higher freeness. Again, these values are smaller than those of pressed handsheets with lower grammages (Olejnik et al. 2021; Makubo 2022). Since the bursting index depends simultaneously on tensile strength and strain, as with specific TEA, it follows a similar pattern across pulp types but shows greater differentiation between hardwood and softwood.

The waxed NBHK trays show no significant increase in burst strength, indicating that wax treatments alone do not compensate for inadequate fiber bonding in hardwood pulps. Overall, the results highlight the crucial roles of pulp type and refining in determining the burst performance of molded trays, with softwood pulps providing greater structural integrity across all freeness levels.

Comparisons between waxed trays and unwaxed trays

Compared with the 435 CSF NBH K pulp (Table 2), the waxed 435 CSF NBHK trays exhibited a 3.1% higher basis weight but showed significant reductions in mechanical properties: a 30.8% lower tensile index, 19.5% lower tensile strain at break, 44.7% lower tensile energy absorption, and a 2.9% decrease in bulk. The bio-wax likely weakened fiber-to-fiber hydrogen bonding, consistent with the behavior of rosin sizing, which compromises dry strength. In contrast, alkyl ketene dimer (AKD) sizing typically has no significant effect on dry strength (Korpela et al. 2021).

Barrier properties of molded trays

Porosity as indicated by Gurley time: Porosity, measured as air permeability and expressed in Gurley seconds, reflects a material's air resistance, with higher values indicating a denser, less porous structure. It is a measure of pore accessibility. As depicted in Fig. 10a and Table 4, Gurley time ranges from a minimum of 18.4 s for the 576 CSF NBHK pulp to a maximum of 125.8 s for the 321 CSF NUBSK pulp, a 584.0% increase.

Across all pulp types, decreasing freeness (i.e., increasing refinement) led to higher Gurley values, indicating reduced porosity. Softwood pulp, particularly unbleached types, consistently yielded trays with greater air resistance than hardwood pulps, likely due to their longer fiber length and better fiber bonding (Gulsoy et al. 2013). Among them, NUBSK pulps exhibited the highest Gurley times across the freeness range. In contrast, NBHK pulps produced trays with the highest porosity. NBSK and SBSK pulps display intermediate performance, with all pulps showing similar sensitivity to changes in freeness, except at the 8% CNF loading.

The addition of cellulose nanofibrils (CNFs) to hardwood pulps also reduced porosity, as evidenced by the increase in Gurley time, which was more pronounced than with refining alone. This can be attributed to CNFs' ability to fill gaps between larger fibers and promote hydrogen bonding, thereby decreasing the effective pore size within the fiber network (Hii et al. 2012; Boufi et al. 2016; Sim and Youn 2016). Statistical analysis confirmed significant differences in Gurley times among the 435 CSF base pulp and CNF-modified samples (5% and 8%), supporting the conclusion that CNFs effectively reduce air permeability.

Figure 10b illustrates the relationship between tray porosity, as indicated by Gurley seconds, and tray bulk (cm^3/g). A general positive correlation is observed between Gurley time and bulk, suggesting that bulkier trays tend to exhibit lower porosity (i.e., greater airflow resistance). Notably, NUBSK trays consistently show high Gurley times across the bulk range, reflecting a relatively blocked pore network that effectively impedes air passage. In contrast, NBHK trays display shorter Gurley times, indicating higher porosity at similar bulk levels. The incorporation of CNFs into an NBHK pulp significantly

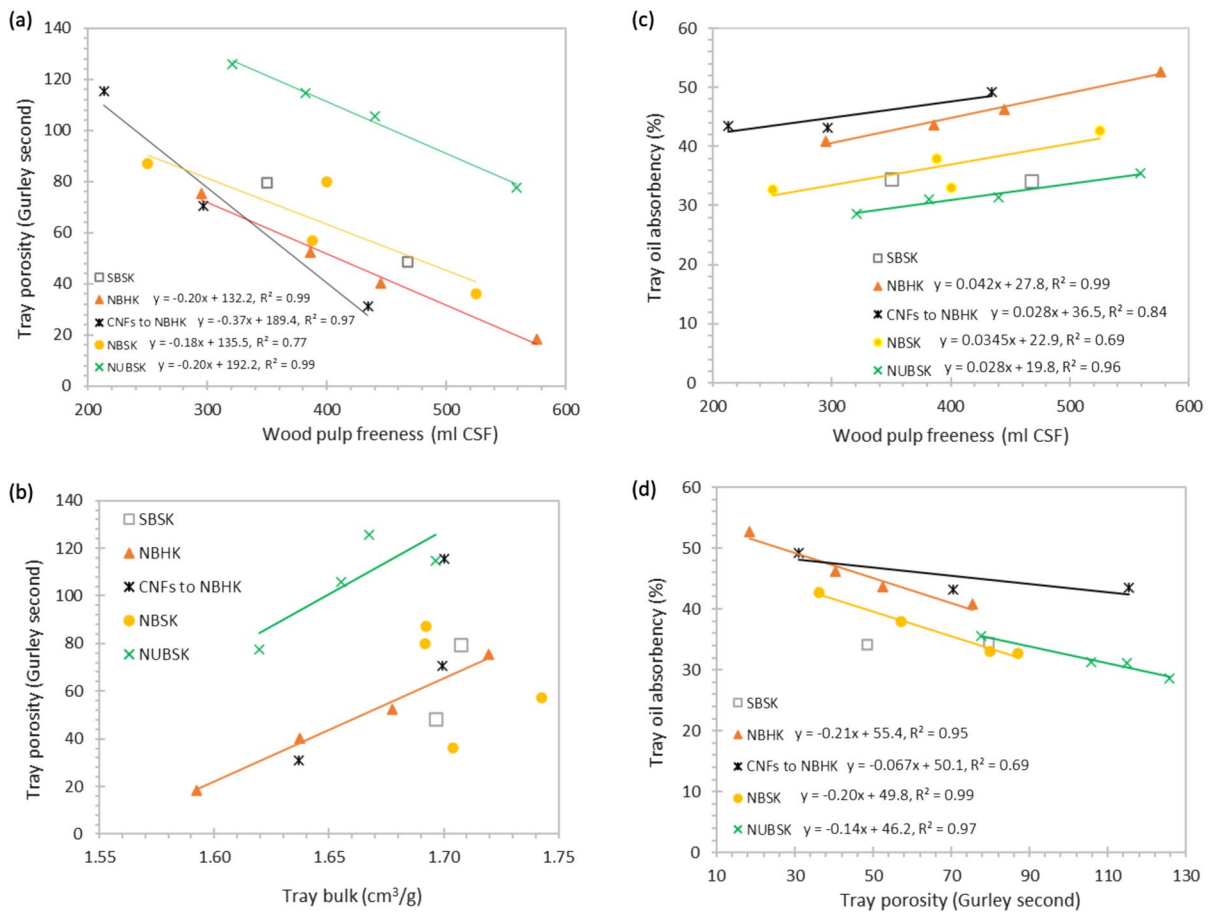


Fig. 10 Barrier properties of molded trays **a** air permeability (Gurley time) with freeness, **b** air permeability (Gurley time) with the bulk, **c** Mazola Corn oil absorbency at 60 °C for 2 min with freeness, and **d** the relationship between oil absorbency and Gurley time

increased both bulk and Gurley time, particularly at 8% loading, demonstrating enhanced air-barrier properties likely due to CNFs blocking microvoids between fibers. Trays produced from SBSK and NBSK pulps exhibited no clear relationship between bulk and Gurley time. Interestingly, the observed trend, where bulkier materials have lower air permeability (higher Gurley time), appears counterintuitive. This may be explained by the formation of a higher volume of closed or blind pores in trays made from finer pulps, resulting in a bulkier structure that is less permeable to air. Although the paper industry often treats air permeability as a surrogate for porosity, this is inaccurate, as blind pores in thick paperboards do not contribute to air permeation. For thick paperboards, calling it air permeability is therefore more meaningful than porosity.

Oil absorbency: Oil absorbency, expressed as a percentage of weight, indicates a material's oil-absorption capacity and is influenced by its void spaces and surface properties. As shown in Fig. 10c and Table 4, trays formed from 576 CSF NBHK pulp showed the highest oil absorbency (52.6%), while those from 321 CSF NUBSK pulp had the lowest (28.6%), a decrease of 45.7%.

Softwood pulps again demonstrated superior barrier performance, particularly the unbleached types, which had both low oil absorbency and high air resistance. Oil absorbency generally decreased with pulp refining. However, adding CNFs to hardwood pulp did not yield improvements comparable to those in softwood pulps. While CNF incorporation reduced oil absorption relative to the base pulp, it did not

surpass the barrier performance of trays made from softwood pulps at equivalent Gurley times (Fig. 10d).

Interestingly, the oil absorbency of all trays did not scale well linearly with air permeability, with $R^2=0.55$, which is smaller than those for each pulp type (Fig. 10d). If porosity alone dictated oil resistance, all samples would exhibit similar oil absorbency at the same Gurley time, and all curves would closely pack across the freeness. This discrepancy suggests that additional influencing factors, such as fiber chemistry and pore connectivity, may be at play. Furthermore, test area differences may contribute to the discrepancy: oil absorption was measured over the entire tray surface, including the flat bottom and corners, which may experience greater compaction and stress during forming, whereas Gurley measurements were limited to the flat bottom section.

Statistical analysis found significant differences in oil absorbency between the base pulp (435 CSF) and CNF-modified samples, but not between 5 and 8% CNF additions. Even so, the CNF-enhanced hardwood pulp showed higher oil absorption across the porosity range than softwood pulp trays. Their lowest basis weights (Fig. 7a), due to insufficient suction times, partially account for their poor oil barriers. Even so, these findings cast doubt on the efficiency of CNFs in achieving the same level of oil resistance as refining or softwood fibers alone.

In summary, for improved oil resistance, unbleached softwood pulps offer the best performance, followed by bleached softwood pulps and CNF-modified hardwood pulps, the least.

Water absorbency: Water absorbency tests revealed a stark contrast in performance. All trays without CNFs failed under hot-water exposure (75 °C for 2 min), becoming saturated or penetrating the underlying wipe. In contrast, trays produced from 435 CSF NBHK pulp with CNF additions (5 and 8%) remained structurally intact. These trays exhibited water absorbency values of 102.8 and 100.4%, respectively.

This enhanced wet performance can be attributed to the high-water retention capacity and network-forming behavior of CNFs. Their ability to entangle and bridge between fibers likely increases wet strength, reduces pore size, and elongates capillary pathways, thereby slowing the pace of water ingress (Boufi et al. 2016).

Comparison with waxed trays: It is essential to note that barrier tests for trays without chemical modification were conducted for shorter exposure times (2 min) than for bio-waxed trays (30 min). Under prolonged test conditions, non-waxed trays, whether treated with CNFs or refined, collapsed due to insufficient barrier properties. The bio-wax treatment substantially improved both oil and water resistance, outperforming any formulation lacking chemical enhancement. This comparison highlights the crucial role of internal treatments and underscores the need for standardized testing protocols that reflect realistic usage conditions. Further refinement of test methods is recommended to accurately evaluate barrier performance in molded fiber packaging.

Effectiveness of refining and CNF addition

Two primary strategies are commonly employed to enhance the properties of paper or molded fiber products: mechanical refining and the addition of CNFs. The most refined hardwood pulp in this study was the 295 CSF NBHK pulp, which had a fines content of 32.7%. In comparison, the base pulp used for CNF reinforcement was a 50:50 blend of 559 mL and 310 CSF NBHK pulps, yielding a freeness of 435 CSF and a fines content of 30.5%. Upon incorporating 5 and 8% CNFs, the resulting pulp mixtures exhibited reduced freeness values of 296 mL and 213 CSF, respectively, and estimated effective fines contents of 33.5 and 35.3%, respectively, calculated proportionally from the base pulp and CNFs (Fig. 5).

Figure 11 compares the effects of these two strategies. Statistical analysis indicates no significant differences in most mechanical and barrier properties between the refined and CNF-reinforced pulps. However, at an 8% CNF loading, notable improvements were observed in tensile index and Gurley time (a measure of air permeability), demonstrating the specific advantages of CNF addition over refining alone. However, increasing the degree of refining will increase the fines content, which may eventually close this performance gap in the tensile index with 8% CNF loading.

As demonstrated, CNF addition leads to a proportional decrease in pulp freeness while delivering molded trays with performance comparable to those made from highly refined NBHK pulp. However, the energy demands of each strategy differ markedly.

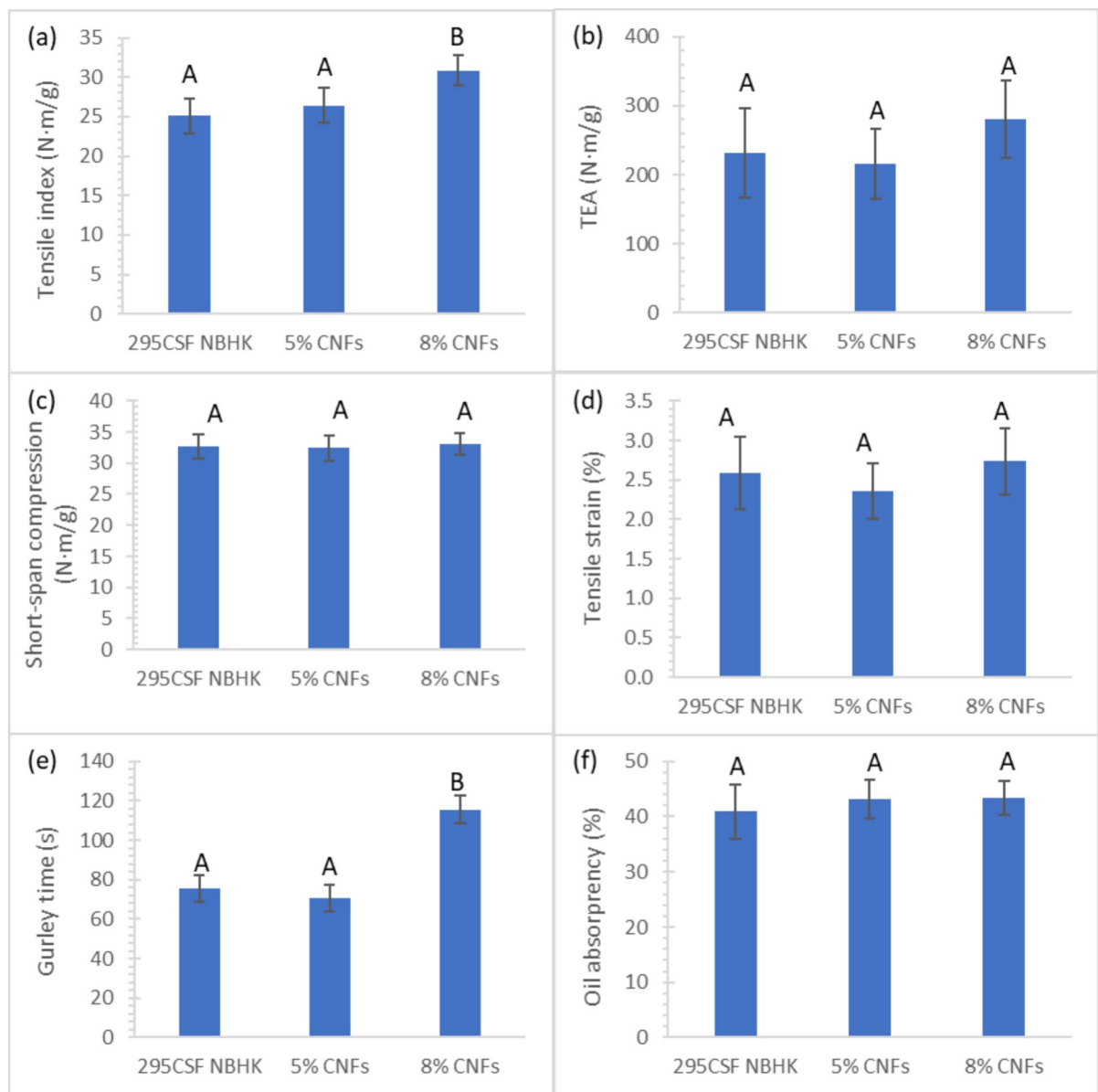


Fig. 11 Characteristic comparisons of refining to 295 CSF and additions of CNFs at 5 and 8%

Figure 12a shows the gross energy consumption of refining NBHK pulp from 576 to 295 mL CSF, consuming 55 kWh per metric ton (MT). In contrast, producing CNFs from bleached softwood kraft pulp to reach a 90% fines level consumes approximately 3420 kWh/MT grossly (Fig. 12b), which translates to an added energy input of roughly 171 kWh/MT for a 5% CNF loading and 274 kWh/MT for an 8% CNF loading. Refining 576 CSF NBHK pulp to 435 CSF

consumes approximately 40 kWh/MT. Hence, the 5% CNF-reinforced 435 CSF NBHK pulp consumes 209 kWh/MT and 310 kWh/MT for the 8% CNF-charged pulp, substantially exceeding the energy required for mechanical refining to achieve similar effects—55 kWh/MT.

In summary, CNF incorporation is a promising strategy to enhance tensile strength and reduce air permeability in molded fiber products. However,

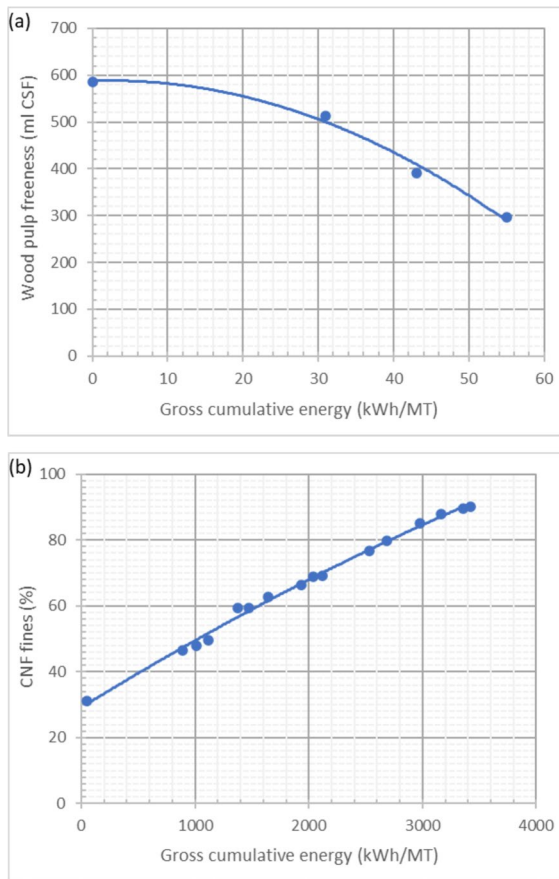


Fig. 12 **a** Gross energy consumption of refining NBHK pulp from 586 mL CSF to 295 mL CSF, and **b** percent fines versus gross energy consumption for CNF manufacture from bleached softwood pulp

this benefit comes at the cost of significantly higher energy consumption than traditional refining. Future work should evaluate the potential of CNF addition in softwood pulp systems to determine whether it offers a more energy-efficient pathway to performance enhancement.

Mechanical and barrier property implications

Comparing the mechanical properties reported in the literature may provide some insights into this study. Five paperboards with grammages ranging from 305 to 502 g/m², all featuring a three-ply structure, comprising a blend core layer of chemi-thermomechanical pulp and kraft pulp and outer plies of kraft pulp, exhibited densities between 0.71 and 0.82 g/cm³.

Their tensile indices ranged from 69 to 77 N m/g in the machine direction and 40–47 N m/g in the cross direction, while their short-span compression indices were approximately 27 N m/g (MD) and 20 N m/g (CD) (Marin et al. 2020). These values indicate that the molded trays evaluated in this study generally exhibited inferior mechanical properties compared to those of paperboard reported in the literature, except for short-span compression indices.

Specifically, the molded trays demonstrated tensile strengths between 6.1 MPa (for trays formed from the 576 CSF NBHK pulp) and 18.1 MPa (for trays with 8% CNF addition), which are significantly lower than the 22–60 MPa reported for paper sheets (Yokoyama et al. 2009; Marin et al. 2020; Jacobsen et al. 2023). Tray densities ranged from 0.58 to 0.63 g/cm³, below the typical density of paper or paperboard, which exceeds 0.70 g/cm³ (Marin et al. 2020; Jacobsen et al. 2023). Jacobsen et al. (2023) also reported that molded samples had significantly lower Young's modulus values, ranging from 0.6 GPa for kraft pulp to 1.2 GPa for TMP, compared to 4–5 GPa for paper sheets hot-pressed at 1.58 MPa.

Dewatering and thermoforming parameters, such as pressure, temperature, and time, could play a crucial role in governing the thermo-hydro-mechano-sorptive interactions between fibers and shaping the fiber network. The reduced mechanical performance of molded trays in this study is likely attributable to the relatively low pressing pressures and times used: approximately 0.30 MPa and 18 s for pre-pressing and 0.56 MPa and 16 s for hot-pressing, as calculated by dividing the applied forces by the expanded area of the tray, which is the same order of magnitude as the standard pressing pressure of 0.345 MPa for preparing handsheets, but much shorter than 7 min of the standard pressing time (TAPPI T205 2024). These pressing pressures and durations are much less than the conditions used in a laboratory investigation, ranging from 2 to 100 MPa under temperatures of 150–200 °C for 10 min, which generated higher mechanical properties but destroyed some desirable paper properties, such as bulk and strain at break (Pasquier et al. 2023). These are also much lower than the pressures typically applied during papermaking. In modern high-speed paper machines, nip pressures during pressing often reach 4–6 MPa to dewater and densify the web, while hard-nip calenders can apply 3–10 MPa to enhance surface smoothness, thickness

uniformity, and bulk properties (Didone et al. 2017). Even up to 27 MPa pressure was applied to densify molded fiber products to achieve the desired oil barriers (Liu et al. 2020). Zume, a startup that produces molded fiber and supplies equipment, which has now been acquired by Genera, recommends setting the hot-pressing pressure at least 11.5 MPa, provided there are no adverse effects, such as aesthetic issues (Horine et al. 2021). Such high pressures promote fiber bonding, densify the fiber structure, and improve the barrier of paper sheets—benefits not fully realized in molded trays pressed at lower pressures.

It is worth noting that the 3D geometry of molded trays presents challenges when using high pressures, including the risk of non-uniform mass distribution, variable thickness, and defects such as blisters or cracks at corners and rims, since the mechanism of applying forces by electric cylinders constrains how large a pressure within a short duration can be applied. The structural and strength development of bulky materials, such as wet fiber mats, under high pressure may require a longer force build-up time, which compromises productivity and is less desirable for low-value molded fiber. The effort of commercializing hot-pressing of the paper web after mechanically dewatering in the papermaking production line has also failed since the paper web does not dwell a sufficient time in a typical hot press nip to allow water evaporation, and the developed steam pressure within the compressed paper under the nip can easily result in an explosive expansion and blistering as it exits the nip (Hubbe 2021). This analysis shows that hot-pressing of a wet thick fiber material must be carefully controlled to ensure the quality. Although high-pressure and long-time conditions were not explored in this study, they may be considered for future work.

Among the pulps tested, the unrefined bleached hardwood pulp (576 CSF) exhibited the lowest tensile index, tensile strain, tensile energy absorption, burst index, and short-span compression strength, along with the highest porosity and oil absorbency, as discussed in the following section, indicating its unsuitability for molded pulp applications without further processing. Hence, it is the best candidate for modification. Freeness control can help achieve desired properties. Mechanical performance improved with either refining or CNF reinforcement, though both approaches are energy-intensive. The increase in mechanical properties with increasing CNF loading

was typically linear, in agreement with the findings of Pego et al. (2020), not exponential, as some previous investigations have reported (Jele et al. 2022). Softwood pulps delivered superior mechanical properties with reduced reliance on refining, suggesting a more energy-efficient route to enhance strength in molded fiber applications. Burst index is the most differential property between hardwood and softwood pulps, while short-span compression strength is the least sensitive to pulp type and refining. Notably, refining did not improve the mechanical properties of the unbleached pulp. Therefore, different pulp types require different processing approaches.

Conclusions

The purpose of this study was to characterize the effects of pulp type and freeness on molding conditions and product quality. The influence of the process parameters on various quality criteria was investigated. The quality criteria considered were physical, mechanical, and barrier properties. This work comprises three investigations. The first one aims to characterize the molding process, while the other two focus on pulp types and freeness, which were varied by either mechanical refining or the addition of CNFs.

The mechanical and barrier properties of molded pulp trays varied with wet thermoforming process conditions. The mechanical properties improved with increased pre-pressing force. Apparent density increased, and oil absorption decreased with higher hot-pressing force, while water absorption decreased with increased hot-pressing temperature. A set of trade-off process parameters was established, including pre-pressing time and force at 18 s and 10 kN, and hot-pressing force, temperature, and time at 17 kN, 220 °C, and 16 s, respectively, resulting in a cycle time of approximately 1 min, including transition times between the stations for a run. This is a trade-off between productivity and product performance: pressing at high pressure for a longer time can improve product performance but reduce throughput. Under these forming parameters, it was confirmed that a commercial bio-based wax, AKD, and a retention-aid formulation significantly reduce water and oil absorption compared with formulations without bio-based wax. Vacuum suction time was the most effective parameter in controlling the

total weight and basis weight of a molded tray. The required suction time increases by more than 2, following a power law, as freeness decreases, from around 2 s for a coarse pulp to 18 s for a CNF-incorporated pulp.

Among the four pulp types with varying degrees of refining considered in this research, the trays made from softwood pulps generally exhibited better mechanical properties, higher Gurley times, and lower oil absorption than those made from hardwood pulps, with the trays made from unbleached softwood pulp having the highest Gurley time and the lowest oil absorbency. Refining proportionally increased Gurley time and decreased oil absorption for all pulps. It enhanced the mechanical properties of trays made from hardwood pulps, whereas its effect on trays made from softwood pulps was minimal and negligible for unbleached softwood kraft pulp. Refining increased the fiber's water-holding capacity, requiring a longer vacuum suction time to maintain a specific tray weight. The bulk of trays, i.e., the volume per unit mass, increased with the degree of refining for hardwood pulps, but apparently not for bleached softwood pulps.

Beyond mechanical refining, incorporating CNFs into pulp suspensions decreased pulp freeness and enhanced the mechanical properties and barrier performance of trays, with effects that increased linearly with increasing CNF loadings rather than exponentially. This approach was less energy-efficient than refining pulp directly. CNF addition increased Gurley time more efficiently than decreasing oil absorbency. At a similar level of pulp freeness or porosity, softwood pulps exhibited better oil resistance than hardwood and CNF-reinforced hardwood pulps. However, trays made from CNF-reinforced hardwood pulps exhibited better water resistance than trays from other pulps, which became fully saturated and deformed immediately after water was poured.

This investigation on a pilot-scale fiber molding system provides foundational insights into the design of pulp type, refining level, formulations, and forming parameters to produce performative molded fiber trays, advancing sustainable food packaging technologies. Future research can be expanded to include non-wood fibers and to systematically compare the effects of direct refining and CNF addition across various pulps. There is also a need to simulate the molding process to optimize process parameters and predict

changes in the tray's properties during molding, pre-pressing, and hot-pressing. The performance criteria of molded fiber trays should also be standardized to promote their market diffusion. This body of knowledge represents a step towards eliminating PFAS use and towards precision manufacturing of molded fiber products.

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Author's contribution J.W. wrote the main manuscript text, and S.P. and C.W. collected the data. All authors reviewed the manuscript.

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Data availability Data is available from the authors upon reasonable request.

Declarations

Competing Interests The authors declare no competing interests.

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