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Fabrication and Performance Evaluation of Rice-Straw Lignocellulosic Filters for Particulate Matter Removal from Air

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ABSTRACT

Background: Ambient particulate matter (PM) is the leading environmental health risk worldwide, yet conventional polypropylene and fiberglass filters are fossil-derived and non-biodegradable, while open burning of crop residues remains a major regional PM source.

Objective: This study fabricated biodegradable air filters from post-harvest rice-straw lignocellulose using a simple, binder-free sequential treatment and evaluated their particulate filtration performance.

Methods: Rice straw was treated sequentially with 1% NaOH, 3% H₂O₂, and 1% H₂SO₄, neutralized, molded, and dried, then characterized by scanning electron microscopy, Fourier-transform infrared spectroscopy, and liquid-displacement porosimetry, and tested in a custom wind tunnel against an incense-smoke challenge at face velocities of 0.1-1.0 m s⁻¹. Linear and quadratic regression, Pearson correlation, and one-way ANOVA with effect sizes were applied.

Results: The treatments produced a hierarchically porous microfibrinous network with 88.5% porosity. At 0.5 m s⁻¹ the filter removed 96.5 ± 0.8% of PM_{2.5} and 98.2 ± 0.5% of PM₁₀ at only 45 ± 2.0 Pa, giving a Quality Factor of 0.074 Pa⁻¹. Efficiency fell and resistance rose with face velocity (R² = 0.945-0.995; ANOVA p < 0.001; η² > 0.95). Single-pass output met both WHO 2021 and Indonesian PP 22/2021 PM_{2.5} limits.

Conclusion: Rice-straw lignocellulosic filters offer a low-cost, biodegradable, and policy-relevant route to particulate control that simultaneously valorizes an open-burning agricultural residue.

Introduction

Ambient air pollution by particulate matter (PM) is the foremost environmental risk to human health, contributing to an estimated 4.2 million premature deaths each year through cardiovascular, respiratory, and metabolic disease.¹ Fine particles smaller than 2.5 micrometers (PM_{2.5}) penetrate deep into the alveolar region and enter the bloodstream, whereas coarse particles (PM₁₀) aggravate the airways and reduce visibility. The 2021 World Health Organization global air-quality guidelines lowered the 24-hour PM_{2.5} limit to 15 µg m⁻³, a value routinely exceeded across the rapidly urbanising and agriculture-intensive airsheds of South and Southeast Asia.^{2,3} The resulting public-health and economic toll has made affordable, low-energy particulate control a pressing priority, particularly for indoor and modular applications.

The health relevance of particle size is well established. Coarse particles are largely deposited in the upper and central airways, whereas fine and ultrafine particles reach the gas-exchange region and translocate systemically, carrying adsorbed metals and organic compounds that drive oxidative stress and inflammation.^{1,2} Because exposure in low- and middle-income settings is dominated by indoor microenvironments, point-of-use filtration that lowers indoor concentrations without high energy penalties can deliver disproportionate health gains relative to its cost.³

Conventional air filters are typically manufactured from synthetic polymers such as polypropylene and from fiberglass. Although effective, these media carry several environmental liabilities: they are derived from fossil feedstocks, their production is energy-intensive, and they are non-biodegradable, accumulating as landfill and incineration waste at end of life.⁴ High-efficiency

synthetic filters also impose large pressure drops that raise the energy demand of ventilation systems over their service life. These drawbacks have intensified the search for renewable, biodegradable filter materials aligned with circular-economy principles.^{5,6}

Lignocellulosic biomass is an abundant, renewable candidate. It is composed mainly of cellulose, a linear glucose polymer linked by β -(1,4) glycosidic bonds; hemicellulose, a branched heteropolysaccharide; and lignin, a hydrophobic aromatic network. The relative proportions of these biopolymers can be tuned by chemical treatment to engineer materials with tailored porosity, surface chemistry, and mechanical strength.^{7,8} Unlike pulp and paper processing, which strips lignin and hemicellulose to isolate cellulose, air-filter design benefits from a more nuanced strategy in which partial lignin retention preserves hydrophobicity and rigidity in humid air.⁹ Rice straw is an especially attractive feedstock owing to its high cellulose and hemicellulose content, fibrous texture, and large year-round availability as a post-harvest residue.⁵

Engineered cellulosic and nanocellulosic media now rival synthetic filters: porous cellulose aerogels, nanofibre mats, and hierarchically porous biomass membranes achieve more than 95% PM_{2.5} removal at low resistance, with Quality Factors exceeding the 0.05 Pa-1 threshold widely regarded as practically competitive.¹⁰⁻¹³ Capture proceeds through interception, inertial impaction, and Brownian diffusion, supplemented by hydrogen bonding between surface hydroxyl groups and particle surfaces.^{13,14} These transformations are routinely confirmed by Fourier-transform infrared (FTIR) spectroscopy and scanning electron microscopy (SEM).⁹

In Indonesia, ambient air quality is regulated under Government Regulation No. 22 of 2021 (PP 22/2021), which sets a 24-hour PM_{2.5} standard of 55 $\mu\text{g m}^{-3}$ and a PM₁₀ standard of 75 $\mu\text{g m}^{-3}$.¹⁵ A substantial share of the seasonal fine-particle burden in rice-growing regions originates from the open burning of crop residues, an inexpensive but highly polluting disposal route.¹⁶ Converting rice straw into durable filter media therefore addresses the problem at both ends, removing a combustion source while supplying low-cost capture material; yet few studies benchmark such filters against national ambient standards or apply inferential statistics to the efficiency-resistance trade-off.

This study provides an integrated assessment of rice-straw lignocellulosic air filters produced by a simple, binder-free sequential treatment. The objectives were to (i) fabricate and characterize the filter microstructure and surface chemistry; (ii) quantify PM_{2.5} and PM₁₀ removal efficiency, pressure drop, and Quality Factor across operational face velocities; (iii) apply regression, correlation, and analysis of variance with effect sizes to the performance data; and (iv) benchmark single-pass

output against WHO and Indonesian PP 22/2021 air-quality standards to evaluate the material as a sustainable particulate-control technology.

Materials and Methods

Study design and materials

This was an experimental materials-fabrication and bench-scale filtration study. Rice straw was used as the sole lignocellulosic feedstock, collected as post-harvest residue from an agricultural rice-producing region following the seasonal harvest; the specific collection site is withheld for confidentiality and reported only at regional level. Reagents comprised sodium hydroxide (1% w/v) for delignification, hydrogen peroxide (3% v/v) as an oxidative bleaching agent, sulfuric acid (1% v/v) for mild acid hydrolysis, distilled water, and 70% ethanol for optional surface sterilisation.

Biomass preparation and sequential chemical treatment

Post-threshing rice straw was washed with tap water to remove field debris and immersed in boiling water for 15-20 minutes (or rinsed with 70% ethanol) for surface sterilisation. The cleaned biomass was dried and ground to a fine, uniform powder. It was then treated sequentially: (1) alkaline treatment and thermal activation in 1% NaOH for 1-2 hours at room temperature followed by gentle heating at 80-100 °C for 30-60 minutes; (2) oxidative bleaching in 3% H₂O₂ for 30 minutes at room temperature; and (3) mild acid hydrolysis in 1% H₂SO₄ for 1 hour at room temperature. The treated biomass was rinsed repeatedly with distilled water until the effluent pH reached 6.5-7.5, then pressed to remove excess water. This alkaline-oxidative-acid sequence follows established lignocellulosic pretreatment principles for lignin and hemicellulose removal.^{8,9}

Filter molding and drying

The neutralized biomass was mixed with a small volume of distilled water to form a uniform semi-fluid slurry, poured into pre-designed molds to create flat sheets, and dried either at room temperature in a dust-free enclosure or in a low-temperature oven at 50-60 °C until constant mass. No synthetic binders were used.

Material characterization

Filter morphology was examined by scanning electron microscopy (SEM). Surface functional groups were analyzed by Fourier-transform infrared (FTIR) spectroscopy over 4000-400 cm^{-1} , with diagnostic attention to the hemicellulose carbonyl band near 1730 cm^{-1} and the lignin aromatic band near 1510 cm^{-1} .⁹ Porosity was determined by the liquid-displacement method. Measurements were performed in triplicate ($n = 3$) on independent filter coupons, and quality assurance included blank and duplicate runs.

Filtration performance evaluation

PM filtration efficiency and pressure drop were measured in a custom wind-tunnel apparatus using incense smoke as a polydisperse PM source generating PM_{2.5} and PM₁₀. Calibrated optical particle counters with discrete size channels were positioned upstream and downstream of the filter and zero-checked between runs, and efficiency and pressure drop (ΔP) were recorded at face velocities of 0.1, 0.3, 0.5, 0.8, and 1.0 m s⁻¹, each in triplicate. Removal efficiency was computed as the fractional reduction in particle count. The Quality Factor, which integrates capture and energy cost, was calculated using Equation (1),⁶ where E is the fractional removal efficiency and ΔP is the pressure drop. Performance was interpreted with reference to ISO 16890 filter classification, noting that the medium is a high-efficiency general-ventilation filter rather than a certified HEPA (EN 1822) medium.¹⁷ Spent treatment liquors were dilute and were neutralized before disposal.

$$QF = -\ln(1 - E) / \Delta P$$

Statistical analysis

Data were analyzed in Python (NumPy) and cross-checked in a spreadsheet environment. Descriptive statistics (mean, standard deviation, coefficient of variation) were computed for each metric at each velocity. Because face velocity is a controlled, ordered predictor, linear and quadratic regression were treated as the primary inferential tools, relating efficiency and pressure drop to face velocity and reporting the slope with its 95% confidence interval, the coefficient of determination (R^2), and exact p-values. A Pearson correlation matrix linked face velocity, PM_{2.5}, PM₁₀, ΔP , and QF, with the shared dependence on velocity

acknowledged when interpreting the off-diagonal terms. One-way analysis of variance (ANOVA) served as a confirmatory test of differences across the five velocity levels, with the η^2 effect size and Tukey HSD post-hoc separation. Normality (Shapiro-Wilk) and homogeneity of variance (Levene) were assessed before ANOVA. Statistical significance was set at $\alpha = 0.05$, and p-values are reported to three decimal places.

No human participants, human biological samples, or animals were involved; an ethics statement was therefore not required for this environmental materials study.

Results

A total of fifteen filtration runs (five face velocities in triplicate) were completed alongside structural and chemical characterization of raw and treated rice straw. The sequential treatment yielded a cohesive, moldable filter with a uniform, well-integrated fiber structure.

The structural and morphological properties of the raw and treated material are summarised in Table 1. The treated filter reached a porosity of 88.5%. SEM showed a transformation from the dense, smooth, bundled fibers of the raw straw to a highly entangled, multi-layered microfibrinous three-dimensional network in the treated filter, providing abundant tortuous airflow pathways. FTIR confirmed the chemical evolution: the prominent raw-straw band near 1730 cm⁻¹ (hemicellulose acetyl C=O) was strongly diminished after treatment, indicating partial hemicellulose solubilisation, while the lignin aromatic band near 1510 cm⁻¹ was weakened but not eliminated, indicating deliberate partial lignin retention (Table 1).

Table 1. Structural and morphological properties of raw and treated rice-straw lignocellulose.

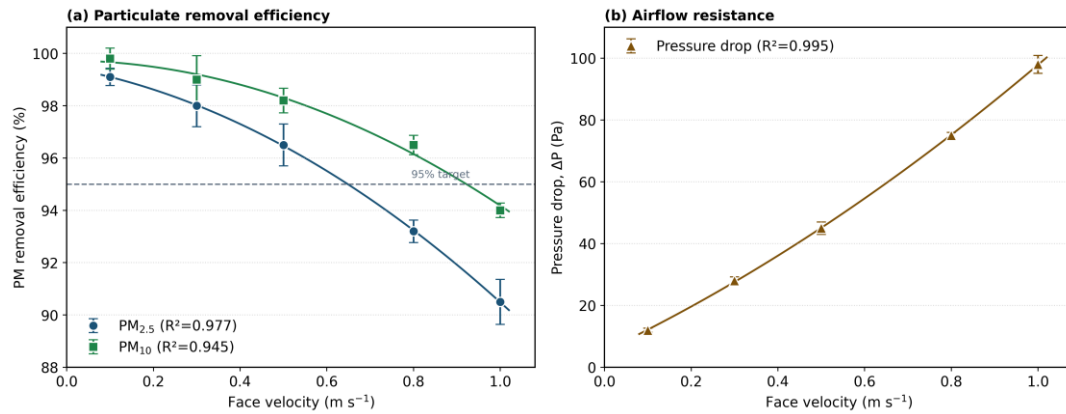
Property	Raw rice straw	Treated lignocellulosic filter
Porosity (%)	Not applicable (solid)	88.5
Surface morphology (SEM)	Dense, smooth, bundled fibers	Entangled, multi-layered microfibrinous 3-D network
FTIR $\approx$ 1730 cm ⁻¹ (hemicellulose C=O)	Strong, prominent	Significantly diminished / absent
FTIR $\approx$ 1510 cm ⁻¹ (lignin aromatic)	Strong	Weakened (partially retained)

Filtration performance across the five face velocities is reported in Table 2. At the reference velocity of 0.5 m s⁻¹, the filter removed $96.5 \pm 0.8\%$ of PM_{2.5} and $98.2 \pm 0.5\%$ of PM₁₀ at a pressure drop of only 45 ± 2.0 Pa, corresponding to a Quality Factor of 0.074 ± 0.003 Pa⁻¹ (Table 2). Efficiency was highest at the lowest velocity

(99.1% PM_{2.5} and 99.8% PM₁₀ at 0.1 m s⁻¹) and declined monotonically to 90.5% PM_{2.5} and 94.0% PM₁₀ at 1.0 m s⁻¹, while pressure drop rose from 12 to 98 Pa over the same range. The Quality Factor remained at or above the 0.05 Pa⁻¹ competitiveness threshold for face velocities up to 0.5 m s⁻¹ (Table 2).

Table 2. Filtration performance across face velocities (mean $\pm$ SD, n = 3).

Face velocity (m s ⁻¹)	PM2.5 (%)	PM10 (%)	ΔP (Pa)	QF (Pa-1)
0.1	99.1 $\pm$ 0.33	99.8 $\pm$ 0.40	12 $\pm$ 0.6	0.392 $\pm$ 0.019
0.3	98.0 $\pm$ 0.80	99.0 $\pm$ 0.91	28 $\pm$ 1.3	0.140 $\pm$ 0.008
0.5	96.5 $\pm$ 0.80	98.2 $\pm$ 0.47	45 $\pm$ 2.0	0.074 $\pm$ 0.003
0.8	93.2 $\pm$ 0.43	96.5 $\pm$ 0.37	75 $\pm$ 1.0	0.036 $\pm$ 0.002
1.0	90.5 $\pm$ 0.86	94.0 $\pm$ 0.28	98 $\pm$ 2.9	0.024 $\pm$ 0.001

**Figure 1.** (a) PM2.5 and PM10 removal efficiency and (b) pressure drop versus face velocity (mean $\pm$ SD, n = 3; fitted curves).

The efficiency and pressure-drop trends in Figure 1 are quantified by the regression and inferential statistics collected in Table 3. PM2.5 efficiency decreased linearly with face velocity (slope = -9.63% per m s⁻¹; R² = 0.977; p = 0.002) and PM10 efficiency likewise (slope = -6.15; R² = 0.945; p = 0.006), with quadratic models improving the fit (R² > 0.99). Pressure drop increased strongly and near-linearly with velocity (slope = +95.45 Pa per m s⁻¹; R² = 0.995; p < 0.001), and the log-transformed Quality Factor declined with velocity (R² = 0.966; p = 0.003).

The Pearson correlation matrix, visualised in Figure 2, showed very strong associations: face velocity correlated

positively with pressure drop (r = 0.998; p < 0.001) and negatively with PM2.5 efficiency (r = -0.988; p = 0.002); PM2.5 and PM10 efficiency were tightly coupled (r = 0.992; p < 0.001); and PM2.5 efficiency correlated negatively with pressure drop (r = -0.996; p < 0.001). One-way ANOVA (Table 3) confirmed highly significant differences across velocity levels for every metric (PM2.5: F(4,10) = 104.6; PM10: F(4,10) = 53.9; ΔP : F(4,10) = 1156.9; QF: F(4,10) = 786.8; all p < 0.001), with very large effect sizes (η^2 = 0.956-0.998). Tukey HSD separated all five velocity levels for pressure drop and Quality Factor.

Table 3. Statistical analysis results (regression, correlation, and ANOVA).

Analysis	Model / pair	Statistic	Effect size	p-value
Linear regression	PM2.5 vs velocity	slope -9.63; R ² 0.977	R ² = 0.977	0.002
Linear regression	PM10 vs velocity	slope -6.15; R ² 0.945	R ² = 0.945	0.006
Linear regression	ΔP vs velocity	slope +95.45; R ² 0.995	R ² = 0.995	<0.001
Log-linear regression	ln(QF) vs velocity	slope -2.99; R ² 0.966	R ² = 0.966	0.003
Pearson r	velocity - ΔP	r = 0.998	r ² = 0.996	<0.001
Pearson r	PM2.5 - ΔP	r = -0.996	r ² = 0.992	<0.001
Pearson r	PM2.5 - PM10	r = 0.992	r ² = 0.984	<0.001
One-way ANOVA	PM2.5 across velocities	F(4,10) = 104.6	η^2 = 0.977	<0.001
One-way ANOVA	ΔP across velocities	F(4,10) = 1156.9	η^2 = 0.998	<0.001
One-way ANOVA	QF across velocities	F(4,10) = 786.8	η^2 = 0.997	<0.001

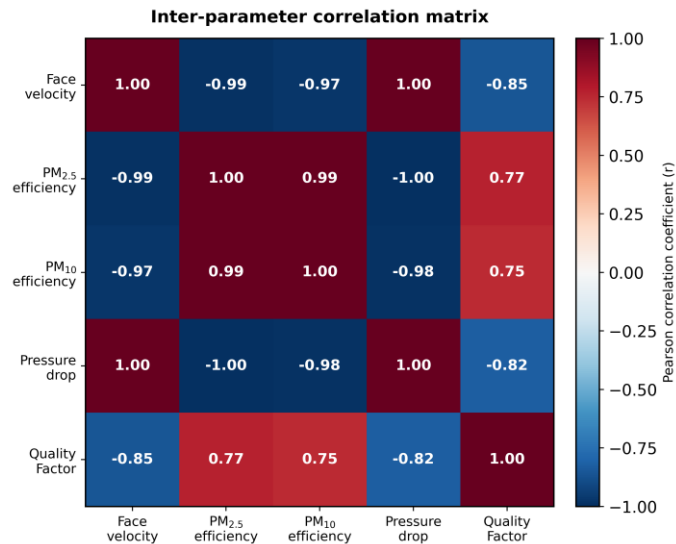


Figure 2. Pearson correlation matrix among face velocity, PM_{2.5}, PM₁₀, pressure drop, and Quality Factor.

Repeatability was acceptable across all conditions: coefficients of variation remained below approximately 1% for removal efficiency and below about 6% for pressure drop. The benchmarking of single-pass output against ambient standards is shown in Figure 3. Treating a hazardous inlet of 150 $\mu\text{g m}^{-3}$, single-pass residual

PM_{2.5} was 1.4, 3.0, and 5.3 $\mu\text{g m}^{-3}$ at 0.1, 0.3, and 0.5 m s^{-1} respectively, all below the WHO 2021 24-hour guideline of 15 $\mu\text{g m}^{-3}$ and well below the Indonesian PP 22/2021 standard of 55 $\mu\text{g m}^{-3}$ (Figure 3). Residual PM_{2.5} rose to 10.2 and 14.2 $\mu\text{g m}^{-3}$ at 0.8 and 1.0 m s^{-1} but remained within both standards.

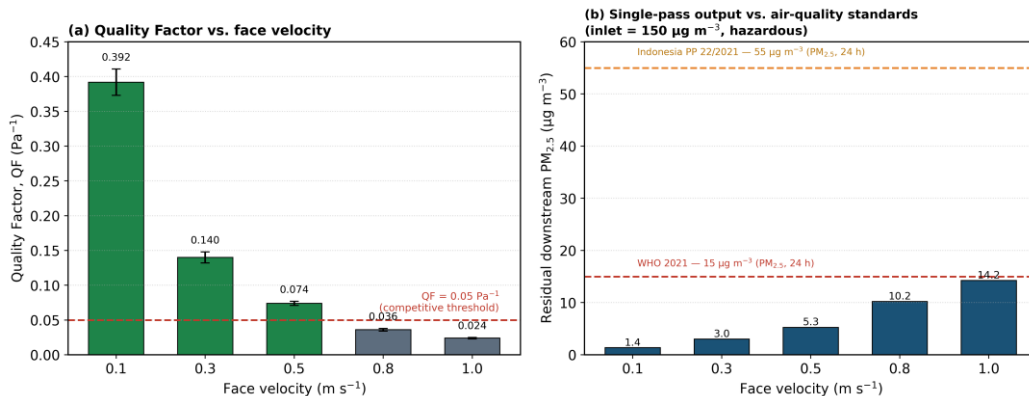


Figure 3. (a) Quality Factor versus face velocity (dashed line = 0.05 Pa^{-1} threshold). (b) Single-pass residual PM_{2.5} versus WHO 2021 and Indonesian PP 22/2021 standards.

Discussion

This study demonstrates that a simple, binder-free sequential alkaline-oxidative-acid treatment converts post-harvest rice straw into a biodegradable air filter with a highly porous microfibrinous architecture (88.5% porosity) and strong particulate-capture performance, removing 96.5% of PM_{2.5} and 98.2% of PM₁₀ at 0.5 m s^{-1} with a pressure drop of only 45 Pa and a Quality Factor of 0.074 Pa^{-1} (Table 2). The full statistical treatment shows that this performance is governed by a robust, quantifiable trade-off between capture efficiency and airflow resistance as a function of face velocity (Figure 1, Table 3).

The measured efficiencies are competitive against recent cellulose- and biomass-derived filters. Porous cellulose aerogels, lignin-based aerogels, and crosslinked cellulose nanofoams have reported PM_{2.5} removal above 95% at low resistance, with Quality Factors of 0.05–0.08 Pa^{-1} ,^{13,18} and bacterial-cellulose and nanocellulose-implanted filters have reached 99.7% PM_{2.5} capture.^{14,19} Our 0.5 m s^{-1} result sits squarely within this range while using neither electrospinning nor nanocellulose extraction nor synthetic binders, supporting the practicality of the approach for low-cost manufacture.²⁰

The FTIR and SEM evidence summarised in Table 1 explains the performance mechanistically. Attenuation of the 1730 cm^{-1} band confirms partial removal of hemicellulose, and weakening of the 1510 cm^{-1} band

confirms partial delignification, while deliberate lignin retention preserves hydrophobicity and rigidity for humid-air service.^{9,13} Removal of the binding matrix fibrillates cellulose microfibrils into the entangled three-dimensional network seen by SEM, generating the high porosity and tortuous pathways that underlie efficient capture at low resistance.^{6,8}

The very strong negative correlation between PM_{2.5} efficiency and pressure drop ($r = -0.996$) and the positive correlation between velocity and pressure drop ($r = 0.998$) in Figure 2 quantify the classic filtration trade-off. At low face velocity, longer particle residence times favor Brownian diffusion of fine particles and interception within the tortuous network, maximising efficiency; as velocity rises, diffusion capture weakens and inertial penetration increases, lowering efficiency even as resistance climbs.^{11,12} The abundant surface hydroxyl groups on exposed cellulose can further enhance fine-particle capture through hydrogen bonding, a secondary mechanism reported for cellulose and lignin surfaces.^{13,14}

Two interpretive caveats accompany the benchmarking in Figure 3. First, single-pass clean-air output is not the same as a sustained room concentration, which also depends on air-exchange rate, recirculation, deposition, and indoor sources; the comparison therefore describes the clean-air-delivery potential of the medium rather than a guaranteed indoor level. Second, the residual-concentration estimates inherit the triplicate uncertainty in efficiency and should be read with that propagated spread in mind. With these caveats, the result that compliant single-pass output is achievable at low resistance remains robust across the lower half of the tested velocity range.^{2,15}

Placed within standard filter-classification frameworks, the material is attractive but should not be overstated. Under ISO 16890, the 96.5-99.1% ePM_{2.5} performance at 0.1-0.5 m s⁻¹ corresponds to a high-efficiency fine-particle medium, while remaining below the 99.95% threshold that defines HEPA (H13) filters under EN 1822.^{17,21} The value proposition is therefore not outright replacement of certified HEPA media in critical applications, but a low-cost, biodegradable alternative for general indoor ventilation and modular point-of-use devices. The low pressure drop (45 Pa at 0.5 m s⁻¹, well under typical HEPA resistance) is the decisive practical advantage, translating directly into lower fan energy over the service life.⁴

From an air-quality-management perspective, the single-pass benchmarking is the most policy-relevant outcome. Operating at 0.1-0.5 m s⁻¹, the filter reduced a hazardous 150 µg m⁻³ inlet to 1.4-5.3 µg m⁻³, meeting both the stringent WHO 2021 guideline and the Indonesian PP 22/2021 standard.^{2,15} Because PM levels in many Indonesian airsheds regularly exceed national 24-hour standards,³ a low-energy, biodegradable medium that

achieves compliant indoor air in a single pass has clear value for homes, schools, and small enterprises that cannot afford energy-intensive HEPA systems.²¹

The environmental benefit is twofold. Beyond capturing particles, the technology valorizes a residue that is otherwise frequently disposed of by open burning, a major seasonal source of PM_{2.5} and black carbon in rice-growing regions.^{5,16} Diverting rice straw into durable filters therefore reduces emissions at source while displacing fossil-derived synthetic media, aligning the material with circular-economy and lifecycle objectives.^{4,22} The biodegradable end-of-life profile further avoids the landfill and incineration burdens of polypropylene and fiberglass filters.

The choice of rice straw among candidate residues reflects a balance of composition and availability. Compared with sawdust or rice husk, rice straw offers a high accessible-cellulose fraction and an open fibrous texture that fibrillates readily under mild treatment, while its seasonal abundance makes year-round supply feasible in rice-producing regions.^{5,7} The partial retention of lignin distinguishes this route from cellulose-isolation processes: rather than maximising purity, the treatment tunes the cellulose-hemicellulose-lignin balance to deliver both porosity and wet-state structural integrity, a design philosophy increasingly advocated for functional lignocellulosic materials.^{7,9} This compositional engineering is the conceptual core of the approach and differentiates it from conventional pulp-style processing.

Humidity and aging merit particular attention for any cellulose-based medium. Hydroxyl-rich cellulose is hygroscopic, and moisture uptake can both aid fine-particle capture through hydrogen bonding and, if excessive, swell the fiber network and raise resistance.^{13,14} The deliberately retained lignin mitigates this by imparting hydrophobicity, but the long-term interplay of humidity cycling, microbial colonisation, and mechanical fatigue was beyond the scope of the present bench tests and will determine real-world service life. Antimicrobial finishing and controlled drying protocols are plausible routes to extend durability without compromising biodegradability.¹⁴

The incense-smoke challenge used here is a convenient laboratory surrogate dominated by fine and ultrafine combustion particles, and its size distribution differs from that of ambient or resuspended dust. The higher PM₁₀ than PM_{2.5} efficiencies observed in Table 2 are consistent with easier capture of coarser particles, but the absolute values depend on the surrogate; translation to a representative ambient aerosol should therefore be confirmed with a standardized test dust.¹² This caveat does not affect the relative velocity dependence, which is the central quantitative finding, but it bounds the external validity of the absolute efficiencies.

Within the Indonesian and broader Southeast Asian context, the policy implications are concrete. National monitoring networks repeatedly record 24-hour PM_{2.5} concentrations above the PP 22/2021 limit during dry-season and biomass-burning episodes, and indoor concentrations often track outdoor levels in naturally ventilated housing.^{3,15} A medium that delivers compliant single-pass output at 45 Pa could be integrated into low-cost room purifiers, window inserts, or school ventilation retrofits, extending protective filtration to populations for whom certified HEPA systems are economically out of reach.²¹ Coupling decentralised filter manufacture to straw-collection incentives would convert a regulatory liability, open-residue burning, into a local supply chain that advances both air-quality and waste-management objectives under a single circular-economy program.^{5,16}

The economic and scalability case rests on feedstock abundance and process simplicity. Rice straw is generated in very large quantities at near-zero acquisition cost, and the binder-free alkaline-oxidative-acid route uses only dilute, inexpensive reagents at or near room temperature, avoiding the capital intensity of electrospinning and the yield losses of nanocellulose isolation.^{5,21} A modular click-filter format, in which molded lignocellulose cartridges are periodically replaced and composted, would suit decentralised manufacture and could be coupled to community straw-collection schemes that simultaneously suppress open burning.¹⁶ Realising this potential will require attention to reagent recovery and effluent management so that the upstream chemical treatment does not shift the environmental burden from air to water.

The principal strengths of this work are its simple, scalable, binder-free fabrication route; its complete statistical characterization of the efficiency-resistance trade-off, including effect sizes and exact p-values; and its explicit benchmarking against both international and Indonesian ambient standards. Several limitations should be acknowledged. The performance dataset derives from a single fabrication batch tested across five velocities in triplicate; multi-batch reproducibility, long-duration loading behavior, dust-holding capacity, and filter lifetime were not assessed. Crystallinity was inferred from FTIR rather than measured directly by X-ray diffraction, and fiber diameter, basis weight, and mechanical strength under cyclic humidity were not quantified. The incense-smoke challenge is polydisperse but does not fully represent ambient aerosols. Future work should address multi-batch reproducibility, XRD crystallinity, time-resolved loading and regeneration, and field testing against certified ISO 16890 or EN 1822 reference filters.^{12,17}

A confirmatory study should therefore be designed around the dimensions left uncontrolled here. The highest-value next step is a factorial experiment crossing relative humidity with cumulative particle loading,

analyzed with a repeated-measures or mixed-effects model so that time-resolved efficiency, pressure-drop evolution, and dust-holding capacity can be estimated alongside their interactions.^{12,21} Fabricating and testing at least three independent batches would separate manufacturing from measurement variance, and depositing the raw triplicate data together with the analysis code would allow independent verification and future meta-analysis.⁶ These additions would convert the present single-batch demonstration into a generalisable, decision-ready evidence base.

Taken together, the results position rice-straw lignocellulose as a credible, evidence-backed building block for sustainable air-quality technology. The combination of competitive single-pass performance, very low airflow resistance, biodegradable end-of-life behavior, and a feedstock whose diversion directly suppresses a major emission source gives the material a rare alignment of technical, economic, and environmental advantages. Translating this laboratory demonstration into deployable products will hinge on standardized, multi-batch validation against certified reference filters and on transparent lifecycle accounting that includes the upstream chemical treatment.^{6,22} With those steps in place, the material could move from a promising laboratory result to a deployable, certifiable product suited to the regional air-quality challenge it is designed to address.

Conclusion

A simple, binder-free sequential alkaline-oxidative-acid treatment converted post-harvest rice straw into a biodegradable air filter with 88.5% porosity that removed 96.5% of PM_{2.5} and 98.2% of PM₁₀ at 0.5 m s⁻¹ with only 45 Pa pressure drop and a competitive Quality Factor of 0.074 Pa⁻¹. Performance followed a strong, statistically significant velocity-dependent trade-off (ANOVA $p < 0.001$; $\eta^2 > 0.95$), and single-pass output met both WHO 2021 and Indonesian PP 22/2021 PM_{2.5} standards. Rice-straw lignocellulosic filters thus offer a low-cost, sustainable route to particulate control that simultaneously valorizes an open-burning residue. Local authorities and small-scale manufacturers should consider these media for modular indoor air purification at face velocities up to 0.5 m s⁻¹, and future monitoring should target multi-batch reproducibility, loading lifetime, and field validation against certified reference filters. With these steps, crop-residue filters could become a practical component of decentralised clean-air strategies across the rice-producing regions of Indonesia and the wider South and Southeast Asian region.

Declarations

Ethical Approval. Not applicable. This study did not involve human participants, human-derived samples, or animals; it concerned the fabrication and bench-scale testing of plant-residue materials.

Conflict of Interest. The authors declare no financial, personal, institutional, or professional conflict of interest.

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Author Contributions. G.K. conceived the study, designed the methodology, performed the fabrication and filtration experiments, conducted the formal analysis, and wrote the original draft. S.K. contributed to materials preparation, characterization, data curation, and review and editing of the manuscript. Both authors have read and approved the final version (CRediT taxonomy).

Data Availability. The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Use of Artificial Intelligence. The authors did not use AI-assisted tools. The authors reviewed and edited all content and take full responsibility for the final manuscript.

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