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Performance of Coconut Waste Interior Panels in Reducing Particulate Matter and Moisture

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Abstract

Indoor Air Quality (IAQ) is a pressing issue in densely populated and poorly ventilated spaces, where pollutants such as PM2.5, PM10, and excessive humidity contribute to health risks including Sick Building Syndrome (SBS). This study proposes a passive and sustainable solution through Coconut Waste Interior Panels (CWIP), made from a 50:50 mixture of activated coconut charcoal (CCAC) and coconut fiber, packaged in perforated wooden boxes. Experiments were conducted in a 27 m³ enclosed room with four scenarios: with/without CWIP and with/without fan circulation, using mosquito coil smoke as the pollutant source. The results showed a significant improvement in indoor air quality (IAQ), with CWIP reducing PM2.5 from 65.67 µg/m³ to 40.27 µg/m³ and PM10 from 82.73 µg/m³ to 49.93 µg/m³ ($p < 0.001$) without fan circulation. A moderate decrease was also observed with fan assistance. Humidity decreased significantly under static conditions. These findings highlight CWIP as an effective, electricity-free, and environmentally friendly alternative, supporting waste utilization and sustainable indoor air quality improvement in resource-limited and environmentally conscious settings.

INTRODUCTION

Most people's time is spent inside the building, where the air inside can be dirtier than the air outside (Fermo et al., 2021; Hou et al., 2022). IAQ is an important factor in maintaining a healthy and pleasant living or working environment (Saraga et al., 2024). There have been many reports of various health problems, mostly related to the respiratory tract, when certain compounds are present in indoor air (Ruiz-Jimenez et al., 2022). Indoor air pollution causes premature deaths (Chojer et al., 2024; Yang et al., 2024). Various sources may directly contribute to pollution in interior spaces, such as emissions from building materials surfaces, equipment, combustion sources, consumer products, and the penetration of contaminants from outside the building. IAQ is frequently affected by common air pollutants, including carbon monoxide (CO), carbon dioxide (CO_2), ozone (O_3), sulfur dioxide (SO_2), nitric oxide (NO), nitrogen dioxide (NO_2), volatile organic compounds (VOC), particulate matter PM2.5 and PM10 (Pourkiaei et al., 2024).

Some indoor PM sources are from furniture and building materials emissions, indoor combustion sources, food sources, resuspension, cleaning, consumer product emissions, secondary-generated pollution indoors, and other goods and activity-related emissions (Saraga et al., 2023). High quantities of aerosol can be produced indoors during cooking. Cooking-related PM emissions will likely accumulate in the kitchen and migrate into the dining room without adequate air ventilation (Chang et al., 2021). PM has been extensively researched indoors (Othman et al., 2024). PM2.5 and PM10 were the most extensively investigated indoor pollutants in source apportionment studies, followed by VOC, NO_2, polycyclic aromatic hydrocarbons (PAH), O_3, and CO (Chojer et al., 2024). PM can be emitted from indoor building materials and can cause respiratory illnesses (Fermo et al., 2021). Indoor air pollution from PM2.5 threatens human health (Yue et al., 2021). In addition to the usual airborne contaminants, the IAQ is also significantly influenced by air temperature and Relative Humidity (Ma et al., 2021; Sadrizadeh et al., 2022). Indoor air pollution is the third most significant contributor to Sick Building Syndrome (SBS). Often, SBS is associated with a lack of ventilation, uncomfortable air temperatures, and humidity (Zainal et al., 2019). Research findings indicate that building occupants experience SBS due to poor indoor air quality. At the same time, the level of relative humidity was strongly correlated with feelings of tiredness and dizziness. In contrast, the amount of PM10 was positively correlated with experiencing a heavy head and eye discomfort (Mansor et al., 2024).

In Indonesia, the environmental health standards for IAQ are governed by the Regulation of the Minister of Health of the Republic of Indonesia Number 2 of 2023, which implements Government Regulation Number 66 of 2014 concerning Environmental Health. These guidelines establish IAQ standards based on physical parameters such as air temperature, lighting, humidity, air velocity, PM10 and PM2.5 concentrations, noise levels, chemical and biological parameters. The standard IAQ parameters examined in this study include humidity levels of 40-60%, a maximum PM10 concentration of 70 µg/m³, and PM2.5 of 25 µg/m³ over 24 h.

Numerous air filtration systems have been developed due to declining indoor air quality (Ahmad et al., 2023), such as mechanical filtration, adsorption, electronic filters, photocatalytic oxidation, and cold plasma (Kumar et al., 2023). Portable air purifiers can decrease indoor PM concentrations in buildings to improve IAQ and health (Cheek et al., 2021). Wealthier households may prioritize health and environmental avoidance and reduce pollution by buying air purifiers, driving cars with fresh air systems, getting frequent health checks, or moving to cleaner locations (Zang et al., 2024). While electrical air conditioners and air purifiers require electrical energy, several alternatives to sustainable air purification technologies utilize natural resources, such as microalgae-based air purifiers (Kumar et al., 2023), botanical filters (Montaluisa-Mantilla et al., 2023), green walls with coconut coir and activated carbon (Pettit et al., 2018), adsorption and photocatalytic oxidation (Yue et al., 2021), and air purifiers that use plants as well as solar panels to move fans (Daghistani, 2023). Reducing indoor air pollution using sustainable materials and methods is urgently needed (Yue et al., 2021), especially in small buildings that don't have a lot of electricity or want to apply low energy building design principle as possible.

Indonesia is the world's largest producer of coconuts, with a total production of 17.13 million tons in 2022 (Food and Agriculture Organization of the United Nations., 2023). The high coconut production in Indonesia also caused much coconut waste, such as coconut shells and coconut coir. Activated carbon made from coconut shells has a highly porous structure and a large specific surface area, enabling effective absorption of air pollutants such as PM, VOCs, and odours. In the context of indoor air quality, its 'performance' specifically refers to the material's absorption capacity and efficiency in removing gaseous and particulate contaminants, supported by its high strength, stable chemical properties, and durability, which contribute to its effectiveness in purifying indoor air (Yue et al., 2021). Coconut coir is a type of coconut waste that has characteristics such as resistance to sea water, microbial attacks, high impacts, and low thermal conductivity (Mahmud et al., 2023). Coconut coir has also been proven to have excellent performance in absorbing and controlling air humidity (Pramitasari, 2016), with its ability to absorb moisture and water (Danso, 2017).

No research has looked at the use of CCAC and coconut coir as passive interior panels to lower PM particles in rooms, despite their widespread usage in environmental applications. Activated carbon has a microporous structure and vast surface area that permits physical adsorption of PM2.5 and PM10 through van der Waals forces and other surface interactions, whereas coconut husks are hygroscopic and help precipitate particles in the air. This study concept is based on the unexplored potential synergy between the two materials in the form of modular panels to enhance indoor air quality. This study examined how well CCAC and coconut coir absorbed moisture and PM within buildings. The materials were packaged in perforated wood panels, which could be merged to make bigger regions to increase IAQ. An air quality monitor was utilized to conduct the experiments in a sealed testing room with a pollutant source to assess CWIP efficacy in lowering PM2.5, PM10, and moisture. The purpose of this study was to quantify PM and humidity reduction in indoor settings with and without CWIP and evaluate its efficacy in a room with and without air circulation (the movement of indoor air).

METHODS

In a previous study, a 3.5x3.4x2.5 m (29.75 m^3) testing chamber was used to test the air cleaner's performance with a pollutant source on one side and a measuring point on the opposite side at 0.5-1.5 m from the floor surface (Law et al., 2024). Another study used an air quality monitor 1.2 m above the floor to conduct trials in the test room (Zhang et al., 2024). The air pollutant source techniques for indoor air pollution research reveal the following source categories: construction materials and furnishings, indoor combustion, cooking, resuspension, cleaning and consumer items, secondary pollution generation, and other products and activities (Saraga et al., 2023). The conventional methods of the air pollutant source remain prevalent (Chojer et al., 2024). Cigarette smoke was used to generate pollutants in laboratory-scale experiments of a biological air purifier (Yewale et al., 2022). Tropical and subtropical regions, especially rural ones, use mosquito coils, which emit VOCs and PMs that may harm health (Li et al., 2023).

The test chamber, measuring 3x3x3 m (27 m^3), is a closed space with no ventilation openings, preventing any exchange of air with the outside environment during measurements. All windows, doors, and air gaps are tightly sealed to create an isolated chamber. Airflow velocity is not measured directly; therefore, the fanless scenario is used to represent minimal airflow, while the fan scenario uses a single fixed speed to produce stable internal air circulation. An air quality monitor was placed on the opposite side of the pollutant source from the mosquito coil's smoke. PM2.5, PM10, and humidity measurements were taken using the Air Quality Monitor DM106A, which employs a laser optical sensor for particle detection with a measurement resolution of ±1 $\mu g/m^3$ and a humidity sensor with an accuracy of ±3% RH, according to the manufacturer's specifications.

A 1 m^2 partition field arranged over the functional interior panels is placed in the middle of the room (Figure 1). The panels are constructed from interlocking wooden boxes, measuring 20x20x12 cm and a wood thickness of 1 cm, resulting in an internal panel space volume of approximately 18x18x10 cm as shown in Figure 2, without any coating. Each box has perforations covering 20% of its widest sides. Inside each panel, a 50:50 of separated CCAC and coconut coir is enclosed within a porous nonwoven fabric. This ratio refers to previous research that combined CCAC and coconut coir in absorbing pollutants, where in full-scale botanical biofilter modules, the 50:50 ratio provides the best VOC removal (Pettit et al., 2018). The coconut coir utilized has a medium density category, whereas the CCAC is granular. A porous structure appropriate for passive adsorption processes is produced by this combination. The double-sided panel's perforations, which enable simultaneous air contact on both sides of the panel, provide the absorber's surface area.

In this study, four measurement scenarios included measurements with and without pollutant absorber panels and with and without a fan (Table 1). The fan used is a standing fan with a speed of 2.5 m/s. Each of these conditions was studied in a testing room with a pollutant source (A), a room with a pollutant source and CWIP (B), a room with a pollutant source and fan (C), as well as a room with a pollutant source, fan, and CWIP (D). Before the measurements were taken, both types of CCAC and coconut coir were dried under the sun for 8 h, while the testing area was conditioned to be free of pollutants by increasing air circulation inside the room. The first 5 min measurement of the initial combustion condition of the pollutant source, the second 5 min adding a fan as a facilitator of the movement of pollutants for the scenario of fan use. For scenarios without the fan, 5 min after the initial measurements are used to wait for the measuring instrument to be activated again. Then the next 70 min measures the pollutant adsorption process and moisture within the data recording time frame every 5 min.

This study did not use mechanical filtration media or commercial air purifiers as positive controls with the focus of the study was to assess the performance of CWIP passive panels. To provide a comparative context, the performance of CWIP is then discussed with reference to the results of other studies on the effectiveness of various filtration media in reducing PM2.5 and PM10, so that the performance of CWIP can still be evaluated within the framework of existing air quality improvement technologies.

The two-sample t-test was performed by comparing all time series measurement data at each point in time between the two scenarios. The difference in degrees of freedom (DF) occurred because the number of valid observations in each scenario differed slightly after sensor data filtering. This analysis used all data per point in time as the observation unit, so that the DF was determined by the number of valid data points in each scenario comparison.

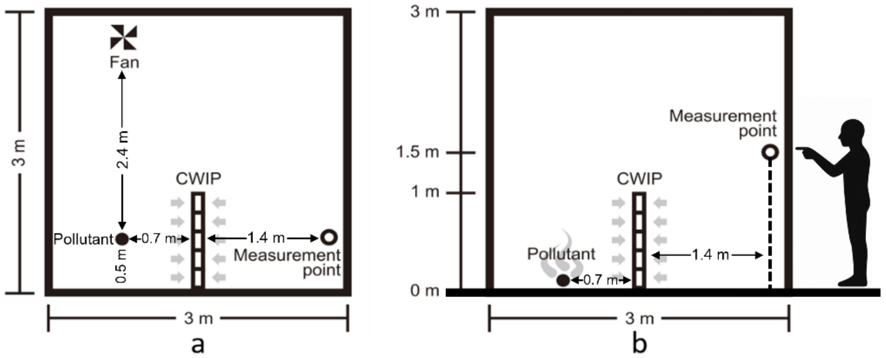

Fig. 1. a.Testing room plan, b.Testing room section

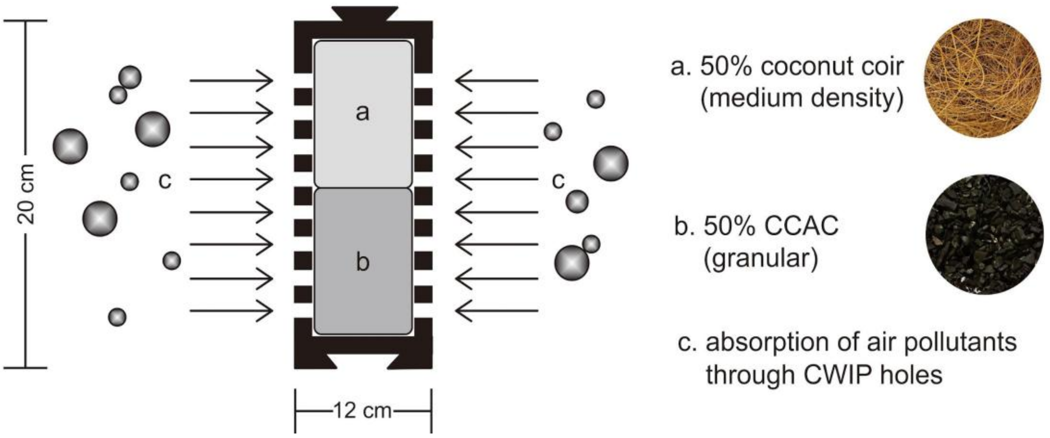

Fig. 2. The Detail of CWIP

Table 1. Measurement scenarios

Scenario	CWIP	Pollutant source	Fan
A	-	V	-
B	V	V	-
C	-	V	V
D	V	V	V

A portion of the adsorption capacity of CWIP material can be restored by re-drying it. In this investigation, both the coconut coir and the CCAC media were sun-dried for 8 h before to each experimental scenario to guarantee that their baseline performance and moisture levels were consistent. While saturated activated carbon may be sun-dried or gently heated to liberate impurities trapped within its pores, coconut husks need to be periodically dried to prevent moisture accumulation. Through this procedure, the materials can be reused, but their adsorption ability may gradually degrade over numerous cycles. An indoor air quality monitoring device may be used to track and regulate the adsorption performance of CWIP.

The effectiveness of the CWIP in reducing some of the physical air pollutants including PM2.5, PM10, and moisture, was evaluated across four test scenarios. The primary objective of this comparison was to measure the reduction in air pollutants and humidity in polluted spaces, both with and without the use of CWIP. The two-sample t-test with Minitab 19 is also used to compare the test results of each scenario, with and without CWIP, as well as with and without a fan. The statistical hypothesis used is the null hypothesis, H_0: there is no effect in the treatment of air, while an alternative hypothesis, H_1: claims that there is an effect in the treatment of air. The rejection criterion is H_0 if the p-value is smaller than α, with $\alpha = 0.05$. The two-sample t-test is employed to ascertain whether the means of two populations are equivalent.

RESULTS AND DISCUSSION

Results

Experiments were carried out under four different conditions to test how well a CWIP with or without a fan absorbs moisture, PM2.5, and PM10. Statistical analysis was used to determine the significance of the performance differences between these scenarios. Specifically, a two-sample t-test was employed to determine whether the observed variations in PM and moisture absorption between the setups were statistically significant. The resulting P-values will indicate the relevance and robustness of the comparisons, providing insight into the operational efficiency of CWIP in varying conditions.

The two-sample t-test yielded a p-value of 0.001, as shown in Table 2, which is significantly lower than the established significance level of $\alpha = 0.05$, indicating a statistically significant difference between data sets A and B. The results showed that the application of CWIP in a room without a fan had a significant effect on humidity levels. Specifically, the room without CWIP had an average humidity of 67.53%, while the room with CWIP showed an average humidity reduction of 63.80%. This difference highlights the significant impact of CWIP in reducing humidity in rooms without fan circulation. In contrast, the two-sample t-test revealed no significant influence of CWIP on moisture levels in a room equipped with a fan. The p-value for the comparison of humidity between scenarios is $p = 0.041$ (< 0.05), indicating a statistically significant difference. These findings underline the varying effectiveness of CWIP depending on ventilation or air circulation conditions.

Table 2. The two-sample t-test results

	Scenario	t-value	DF	p-value
Moisture	A & B	3.73	26	0.001
	C & D	0.85	27	0.401
PM2.5	A & B	19.61	27	0.000
	C & D	15.13	18	0.000
PM10	A & B	19.37	27	0.000
	C & D	12.34	18	0.000

Table 3. The air quality of 4 scenarios

Minute	Moisture (%)				PM2.5 (µg/m^3)				PM10 (µg/m^3)			
	A	B	C	D	A	B	C	D	A	B	C	D
0	75	70	74	73	72	49	75	65	72	39	94	85
5	72	68	70	70	67	43	75	66	83	54	95	87
10	71	66	69	68	71	46	77	64	88	58	98	81
15	69	65	68	67	70	43	72	61	92	54	93	78
20	68	64	67	66	66	42	73	59	83	54	93	78
25	67	63	66	65	68	41	75	57	88	52	98	74
30	67	63	66	64	65	39	74	61	81	51	94	77
35	66	63	65	64	65	39	74	57	84	50	92	71
40	66	63	64	64	65	37	73	57	84	47	94	72
45	66	62	64	63	62	36	72	59	78	47	94	77
50	66	62	64	63	65	36	74	57	86	47	92	76
55	65	62	64	63	63	38	73	56	83	50	91	71
60	65	62	64	63	62	38	72	58	81	47	91	74
65	65	62	64	63	62	38	73	57	79	49	94	71
70	65	62	64	63	62	39	73	55	79	50	96	70
Average	67.53	63.80	66.20	65.27	65.67	40.27	73.67	59.27	82.73	49.93	93.93	76.13

Table 3 is the PM and moisture data for each scenario. It illustrates the average humidity levels in a room equipped with a fan or a room with an air circulation condition, comparing conditions without and with CWIP. The humidity levels in these rooms were 66.20% for scenario s without CWIP and 65.27% for scenario D with CWIP. These findings are in line with previous research, which shows that coconut coir has excellent moisture absorption properties (Pramitasari, 2016). Additionally, the use of coconut coir offers other benefits, such as passive cooling, which has been shown to lower indoor air temperatures in buildings (Sigi Kumar et al., 2023). The use of CWIP has a significant impact on the reduction of PM2.5 pollutants indoors. This can be seen from the p-value of the two-sample t-test, which is lower than α (0.05). This difference in PM2.5 levels in room without CWIP and those with CWIP, with scenario A at 65.67 µm/m^3 and scenario B at 40.27 µm/m^3. The p-value result is 0.000 on the effect of using CWIP in a room with a fan on reducing PM2.5 pollutant levels. This shows that the use of CWIP significantly reduces the level of PM2.5 in a room with a fan. The levels of PM2.5 pollutant in scenarios C and D are 73.67 and 59.27 µm/m^3, respectively. As the p-value is smaller than α (0.05), which is 0.000, the application of CWIP clearly influences the decrease of PM10 pollutants. Table 3 further displays the variations in PM10 pollution values across scenarios A and B, 82.73 and 49.93 µm/m3, respectively. With a p-value of 0.000, CWIP greatly influences the decrease of PM10 in rooms with fans in scenarios C and D. In scenarios C and D, the average PM10 pollution levels are respectively 93.93 and 76.13 µm/m^3 .

The efficacy of CWIP in enhancing indoor air quality and reducing dispersed particles is illustrated in Figure 3. CWIP obtained a 39.67% decrease in the concentration of PM10 in the room without a fan, which was the most significant reduction. This achievement was closely followed by a reduction in PM2.5, indicating the system's strong ability to filter out delicate PM. In the room equipped with a fan, CWIP still yielded substantial reductions, although its performance was slightly less pronounced. The average percentage decrease was 19.56% for PM2.5 and 18.94% for PM10, demonstrating that even with fan airflow, CWIP can mitigated the PM levels. These results demonstrate the ability of CWIP to significantly improve indoor air quality, especially in settings without strong air circulation, while still offering benefits in ventilated environments. The results show the CWIP's contribution to creating healthier indoor environments by effectively managing PM and humidity. The data demonstrate that the moisture content decline curve began to level out around the 45th minute, indicating that coconut coir may have neared saturation or achieved a brief adsorption equilibrium point. This plateau phenomena correlates with the hygroscopic features of natural fibers, where the absorption rate reduces as the water concentration in the material approaches its maximum capacity.

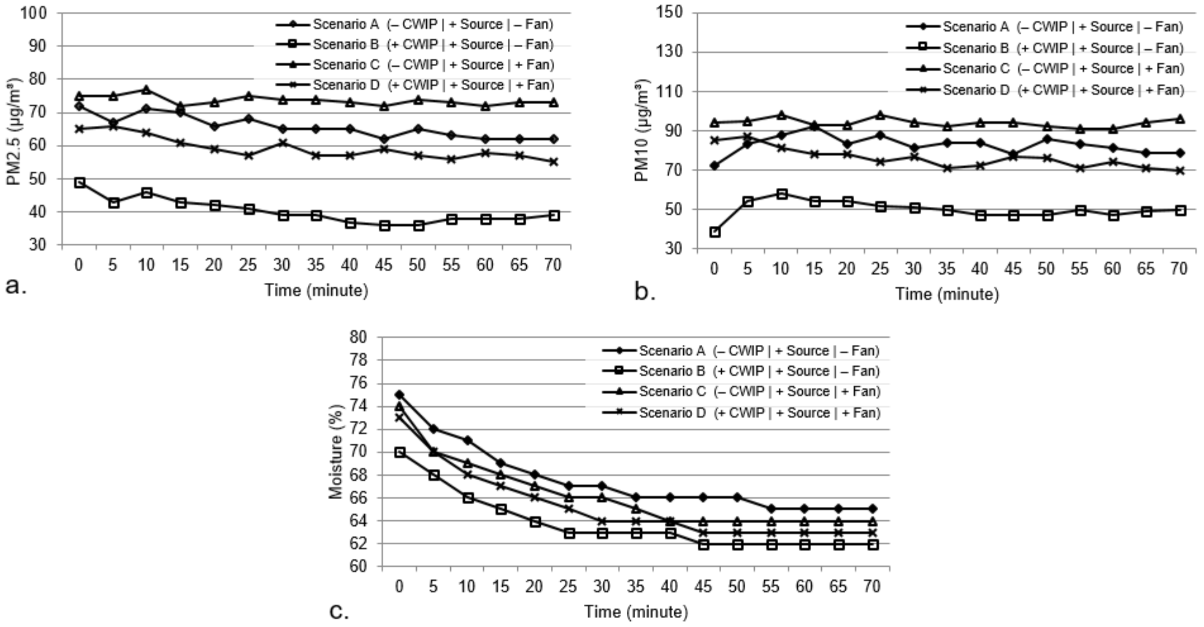

Fig. 3. The PM and moisture data of 4 scenarios: a. PM2.5, b. PM10, c. Moisture

Discussion

CCAC and coconut coir panels have combined as effective interior materials for improving IAQ and encouraging sustainable construction practices. These materials, generated from coconut trash, have considerable environmental and functional benefits, from PM reduction to humidity control. Because of its magic surface area and superior adsorption ability, activated carbon, a substance made from coconut shells, has demonstrated tremendous potential in lowering indoor PM2.5 and PM10 levels. Because of these capabilities, it can effectively capture airborne particles, contaminants, and other dangerous chemicals, providing an eco-friendly answer to problems with indoor air filtration. The carbon produced from coconut shells has an extensive network of pores, essential for efficient adsorption. The activation process, which often includes chemical agents such as phosphoric acid (H_3PO_4) or potassium hydroxide (KOH), enhances pore expansion, increasing adsorption capacity and improving pollutant capture (Aprilianti et al., 2023; Umweni et al., 2023). A higher iodine number, a key indicator of adsorption strength, confirms the material's efficiency (Ohimor et al., 2021; Umweni et al., 2023). CCAC is very effective in adsorbing gaseous pollutants such as CO and CO2, and particulate matter such as PM2.5 and PM10 (Oloriegbe et al., 2022; Suleiman & Isah, 2023). Compared with other activated carbons obtained from agricultural wastes, coconut shell-based carbon demonstrates higher adsorption performance, making it good for air purifier systems (Oloriegbe et al., 2022). The production of CCAC is feasible and contributes to environmental sustainability by reusing coconut waste. Increasing production could be important in reducing indoor air pollution (Suleiman & Isah, 2023). In addition, the efficacy of coconut-based carbon can be further optimized by adjusting factors such as the pollutant concentration, contact time, and dosage (Oloriegbe et al., 2022).

Coconut fiber is becoming more and more well-liked as a sustainable building material, alongside activated carbon. This material offers a range of benefits as a building element, including moisture control, thermal insulation, and mechanical strength, making it a good alternative for sustainable construction projects. Coconut coir panels have a thermal conductivity of 0.08-0.15 W/(mK), comparable to other natural and synthetic insulating materials (Mucsi et al., 2022). This feature is essential for controlling humidity level and indoor air temperatures. In addition, increasing the coconut fiber content can boost its flexibility and internal bonding, consequently enhancing its structural integrity and durability (Mucsi et al., 2024). The natural moisture absorbing properties of coconut coir show it highly effective in controlling humidity. Studies have shown that coconut coir can reduce water absorption in compacted and stabilized earth blocks, demonstrating its potential in controlling indoor humidity levels (Peter Olugbenga Omotainse et al., 2024). Using coir panels in buildings is further supported by their ability to maintain low indoor air humidity and temperature in evaporative ventilation systems (Natesan et al., 2024). Using coconut coir, a byproduct of coconut processing, reduces waste and increases environmental sustainability (Wolfgang Stelte et al., 2023). Developing coir-based panels as a renewable, biodegradable alternative to conventional building materials aligns with the growing demand for environmentally friendly construction solutions (Mucsi et al., 2022).

CWIP in this study is designed as a modular two-sided panel that can be applied as a partition wall or a one-sided panel on a wall or other interior elements. The openable panel design allows the absorbent media to be replaced or dried periodically as part of maintenance. Coconut coir has natural antimicrobial properties due to its tannin and lignin content, while CCAC captures particles thru adsorption mechanisms and requires regeneration when saturated. The combination of these two materials enhances the potential of CWIP as a passive interior architectural element compatible with the space design.

The research findings indicate that airflow strongly influences the effectiveness of CWIP. In rooms with fans, air particles are carried by air movement, thus reducing contact time with the panels. This also causes the decrease in humidity to become insignificant because coconut fiber cannot optimally absorb water vapor under high air circulation conditions. The previous study shows that ceiling fans can increase particle dispersion in enclosed spaces and do not always direct them toward ventilation openings, so particle concentrations can remain high (Nazari et al., 2024). These findings are aligned with the results of this study, where only a small fraction of particles were absorbed by CWIP when the fan was used.

In a room without a fan, CWIP reduced PM2.5 by ±38.7% and PM10 by ±39.6%, while in a room with a fan, the reductions were ±19.5% and ±18.9%, respectively. Humidity decreased by ±5.5% without a fan and ±1.4% with a fan. This indicates that CWIP is more effective in indoor low airflow conditions, as the air-material contact time increases.

The effectiveness of CWIP is influenced by the surface area of the absorber, the volume of the medium, the size of the perforations, and the air contact speed. Although this study has not yet established panel-to-space volume ratios such as ACH or absorber/m², initial findings suggest that increasing the panel area has the potential to improve effectiveness until the material reaches saturation. The use of CWIP as a full wall covering or modular panels also impacts surface porosity, moisture buffering capacity, and the thermal dynamics of the space. Biomass-based materials like CWIP need to be replaced or regenerated periodically, as shown in previous biofilter studies (Yewale et al., 2022).

From an architectural design standpoint, the panel coverage needs to be regulated to avoid declining returns and to address the interaction of CWIP with natural ventilation, especially in hot and humid areas. Furthermore, CWIP may be included into passive-mechanical hybrid systems; in contrast to excessive turbulence, which decreases adsorption efficacy, low-speed fans, cross ventilation, or small-flow mechanical ventilation can extend the air's contact time with the panels. This approach provides opportunities for further research on placement strategies and optimizing the CWIP area in various spatial configurations.

CONCLUSION

This research shows that CWIP, consisting of CCAC and coconut coir, have strong potential as a passive interior building element to improve IAQ. In the room with no air circulation, CWIP reduced PM2.5 by ±38.7%, PM10 by ±39.6%, and humidity by ±5.5%. Under conditions with a fan, its effectiveness decreases to ±19.5%, ±18.9%, and ±1.4%. This result confirms that CWIP is more effective in spaces with low airflow, when the air-material contact time is far more optimal.

PM absorption and indoor humidity control are made possible by the properties of CCAC material and coconut coir, which eliminate the need for extra energy for electric air filtration. CWIP is better suited for enclosed areas with low speed air circulation or ventilation, including bedrooms, study rooms, tiny home offices, or rooms without active air conditioning, while its efficacy declines in areas with high air circulation.

CWIP has the architectural potential to be applied as wall panels, interior partitions, or other architectural elements inside the buildings. However, design guidelines are needed regarding panel area, panel-to-room ratio, and ideal airflow conditions for this system to be effectively implemented and scalable in various building contexts.

This study has several limitations, including the absence of temperature recording, the un-evaluated ability of CWIP to absorb other indoor air pollutant, and the relatively short testing duration. Further studies need to include temperature monitoring, long-term testing, and the testing of other pollutant absorption.

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