Development of Heme- and Biochar-Reinforced Porous Bio-Composite Bricks from Durian Peel for Enhanced Adsorption of PM2.5 and Air Pollutants

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ABSTRACT

Fine particulate matter (PM2.5) is a persistent air-quality challenge because particles in this size range can remain suspended in air and can penetrate deeply into the respiratory system. At the same time, durian peel is an abundant lignocellulosic agricultural residue in Thailand that can be converted into carbon-rich biochar. This study proposes a porous bio-composite brick that integrates durian-peel-derived biochar with a cementitious matrix, zeolite, natural fiber, and a heme-based functional additive. The design is based on a hierarchical pore concept: interconnected macropores are intended to preserve airflow pathways, while the micro- and mesoporous structure and surface functionalities of biochar provide additional pollutant-interaction sites. The experimental program will vary biochar loading from 0 to 20 wt% on a defined dry-mass basis and will quantify bulk density, open porosity, water absorption, compressive strength, surface morphology, and controlled PM2.5 removal. A blank chamber and non-functional control will be used to separate true material effects from particle settling, leakage, humidity effects, and sensor drift. The study is deliberately designed as a multi-objective optimization problem rather than assuming that the highest biochar loading will provide the best performance. The expected outcome is a reproducible formulation that balances pore connectivity, mechanical integrity, and particulate-removal performance while converting an agricultural residue into a higher-value environmental construction material.

Keywords: Durian peel biochar/ Porous bio-composite/ PM2.5/ Adsorption/ Pore connectivity/ Zeolite/ Heme-based functional additive/ Sustainable construction material

1. INTRODUCTION

Air pollution by fine particulate matter (PM2.5) is a major environmental engineering challenge because particle concentration can vary rapidly with local emissions, weather, ventilation, and atmospheric conditions. Conventional responses focus on source reduction, filtration, ventilation, and atmospheric management. A complementary strategy is to incorporate environmental functionality into porous building materials so that architectural surfaces can interact with polluted air without requiring a separate filtration unit.

Biochar is a carbon-rich solid produced from biomass under oxygen-limited thermochemical conversion. Its surface chemistry and pore architecture depend on feedstock, pyrolysis conditions, particle size, and any activation or modification process. Research on biochar-cement composites has identified both sustainability opportunities and engineering trade-offs involving dispersion, pore structure, strength, and durability [1-3].

Durian peel is a particularly relevant feedstock because it is a large-volume lignocellulosic residue. Previous studies summarized in the project source have demonstrated that durian-peel-derived biochar can be engineered to develop porous structures and oxygen-containing surface functionalities,

with reported adsorption mechanisms including pore filling, hydrogen bonding, electrostatic interactions, and π-π interactions for aqueous contaminants [4, 5]. These findings support the choice of durian peel as a carbon precursor, but they do not prove PM2.5 removal; particulate performance must be measured directly in the present study.

The key engineering challenge is therefore not simply maximizing total porosity. A material can have a high void fraction while still providing poor mass transfer if fine particles block the connecting pore throats. Recent work on biochar-modified permeable concrete indicates that excessive fine-biochar loading can reduce permeability through pore blockage [7]. The proposed study consequently treats accessible pore connectivity, mechanical integrity, and particulate removal as linked performance variables.

2. RESEARCH RATIONALE AND SCIENTIFIC NOVELTY

The proposed research combines four functions within one material platform: (1) durian-peel biochar as a carbonaceous porous phase, (2) zeolite as an additional porous mineral phase, (3) a heme-based material as a separately controlled functional additive, and (4) a cementitious matrix with natural fiber reinforcement to retain structural form. The novelty is not the use of any one ingredient in isolation; it is the systematic structure-property-performance evaluation of an agricultural-waste-derived porous brick under controlled airflow.

A further strength is the use of a predefined formulation window and objective decision criteria. The project will compare a non-biochar control with 5, 10, 15, and 20 wt% biochar formulations. The preferred material will be selected using a multi-criteria framework rather than by choosing the formulation with the largest PM2.5 reduction alone. This approach directly addresses the expected trade-off between accessible porosity and compressive strength.

3. RESEARCH GAP

- Existing biochar-cement research is concentrated heavily on water purification, mechanical properties, carbon sequestration, and durability; fewer studies directly evaluate a brick-scale porous composite as a passive PM2.5-interacting material.
- Durian-peel biochar has demonstrated adsorption potential, but that performance must be translated from powdered adsorbent systems to a mechanically stable porous composite.
- Increasing biochar loading does not necessarily maximize useful porosity because fine particles can occupy or block interconnected voids.
- The environmental and mechanical performance of the material should therefore be evaluated together, with pore connectivity treated as a critical design parameter.

4. RESEARCH QUESTIONS

- What biochar loading provides the most favorable balance between open porosity and compressive strength?
- How does biochar particle size affect accessible pore connectivity and PM2.5 removal performance?
- Does incorporation of the selected heme-based additive and zeolite measurably alter particulate-removal performance relative to the control?
- How do airflow rate, contact time, and initial PM2.5 concentration influence apparent removal efficiency?
- Can the porous bio-composite brick achieve repeatable particulate-removal performance without unacceptable loss of structural integrity?

5. OBJECTIVES

- Produce and characterize biochar derived from durian peel under controlled oxygen-limited pyrolysis.
- Develop porous bio-composite brick formulations with controlled biochar loading.
- Quantify open porosity, bulk density, water absorption, and compressive strength.
- Evaluate controlled PM2.5 removal using a reproducible airflow test system.
- Determine the formulation that provides the best multi-objective balance among pore connectivity, mechanical integrity, and particulate-removal performance.
- Assess the potential for agricultural-waste valorization by converting durian peel into a functional construction material.

6. HYPOTHESIS

A moderate biochar loading will increase accessible surface area and pollutant-interaction sites without excessively blocking interconnected pores. Therefore, the study will test whether intermediate formulations differ from the zero-biochar control and the highest-loading formulation when PM2.5 removal is evaluated together with compressive strength and pore connectivity. This is a testable hypothesis, not a reported experimental result.

7. SIGNIFICANCE OF THE STUDY

- Environmental significance: converts durian-processing residue into a higher-value material and provides a route for integrating environmental functionality into construction surfaces.
- Engineering significance: investigates the relationship among biochar loading, pore connectivity, density, water absorption, and compressive strength rather than treating filtration performance as an isolated property.
- Methodological significance: uses blank and material controls, replicate specimens, controlled airflow, and quantitative particle monitoring to strengthen the validity of PM2.5 comparisons.
- Practical significance: identifies a candidate formulation that could be further evaluated for non-load-bearing blocks, architectural panels, or passive environmental surfaces after appropriate standards testing.

8. SCOPE OF THE STUDY

8.1 Study Location

Material preparation and preliminary testing will be conducted in an appropriately equipped school or partner laboratory. Advanced characterization, if required, may be performed through a qualified university laboratory.

8.2 Study Duration

The planned study period is 16 weeks, covering literature review and risk assessment, biochar preparation, formulation and molding, curing, physical and mechanical characterization, controlled PM2.5 testing, replication, statistical analysis, optimization, and final reporting.

8.3 Study Variables

The experimental variables are defined consistently throughout the manuscript. Independent variables include biochar loading, particle-size fraction, and the presence of selected functional additives. Dependent variables include open porosity, bulk density, water absorption, compressive strength, and PM2.5 removal. Controlled variables include specimen geometry, curing conditions, mixing procedure, airflow rate, exposure time, initial particle concentration, temperature, relative humidity, and measurement protocol.

8.4 Expected Benefits

- Provide a reproducible method for preparing durian-peel biochar and incorporating it into a porous composite.
- Generate quantitative evidence linking biochar loading to pore structure, mechanical integrity, and PM2.5 performance.
- Identify a formulation with a defensible balance between environmental function and structural performance, subject to experimental validation.
- Support future development of agricultural-waste-derived materials for environmental applications.

9. DEFINITION OF TERMS

The operational definitions used throughout this study are summarized in Table 1.

Table 1. Definition of terms used in the study

Term	Operational definition
Biochar	A carbon-rich material produced by thermochemical conversion of biomass under oxygen-limited conditions.
Open porosity	The fraction of a material's volume associated with voids that are accessible to the measurement medium.
Pore connectivity	The degree to which pores are interconnected sufficiently to permit fluid or air transport through the material.
PM2.5	Fine particulate matter with an aerodynamic diameter of approximately 2.5 μm or smaller.
Bio-composite brick	A composite construction specimen containing a cementitious matrix and bio-derived functional components.
Blank chamber	A test run without the material specimen, used to quantify particle decay caused by settling, leakage, or other chamber effects.
Multi-objective optimization	A decision process that evaluates several performance criteria simultaneously rather than selecting a material using one metric alone.

10. MATERIALS AND EQUIPMENT

The material system and the engineering role of each component are summarized in Table 2. The heme-based additive is intentionally specified by material identity rather than biological source; its exact chemical identity, purity, particle size, and safety classification must be verified from the supplier or laboratory specification before experimental use.

Table 2. Materials and equipment components and their engineering roles

Component	Role	Key design consideration
Portland cement	Primary binder	Maintains matrix cohesion and specimen shape
Durian peel biochar	Carbonaceous porous phase	Provides porous surface and pollutant-interaction sites
Zeolite	Porous mineral phase	Adds adsorption-active mineral surface
Heme-based additive	Functional additive	Evaluated as an independent formulation variable
Cellulosic/natural fiber	Crack-control reinforcement	Keep fiber length and loading consistent
Water	Hydration and processing medium	Maintain a constant water-to-binder protocol

The following figures document the source material and process components used to frame the proposed material system. Figure 1 shows the durian peel feedstock selected as the biomass precursor.

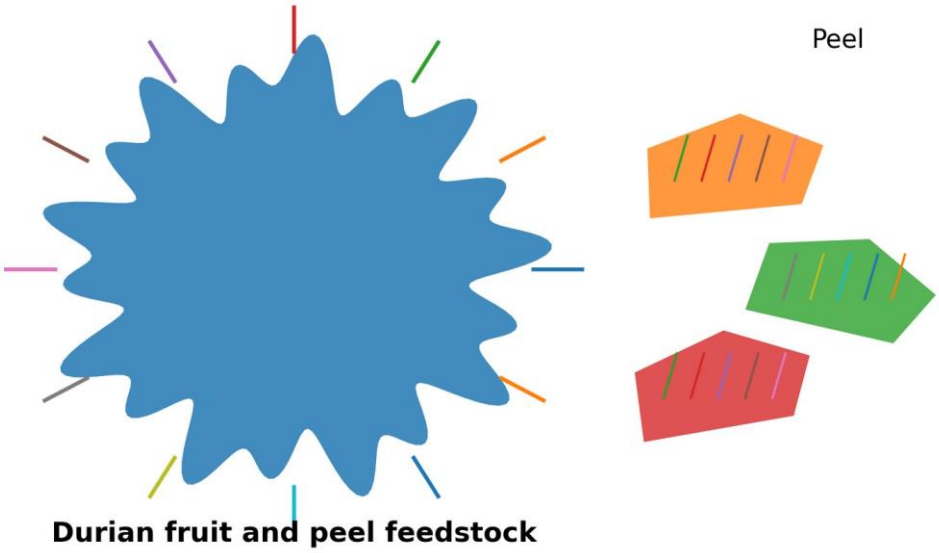

Figure 1. Durian peel feedstock selected as the biomass precursor (Source: Food Waste Hub Thailand, "การพัฒนาและเพิ่มมูลค่าเปลือกทุเรียน" (durian peel image), 2024. https://www.foodwastehubthailand.com/ready-to-use/เปลือกทุเรียนเพื่อเป็น/)

Figure 2 shows the oxygen-limited conversion pathway used as the conceptual basis for producing porous biochar.

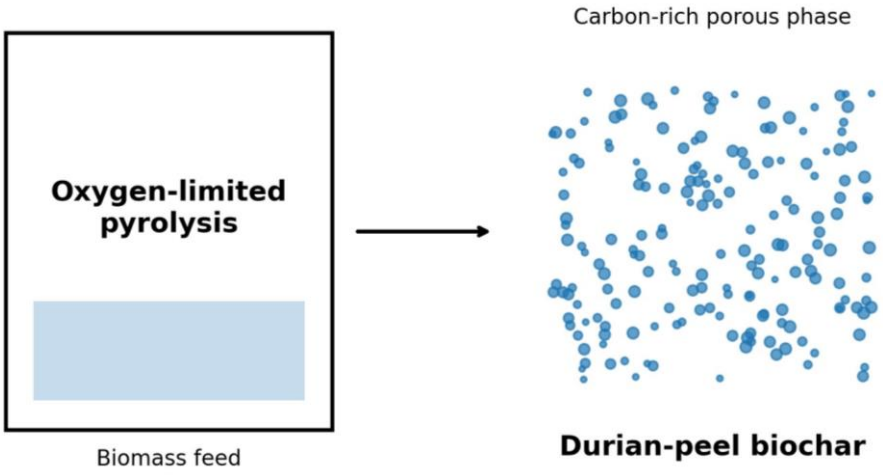

Figure 2. Oxygen-limited conversion of durian peel into porous biochar (Source: K. Salo.85, "Biochar.jpg," Wikimedia Commons, CC BY-SA 4.0. https://commons.wikimedia.org/wiki/File:Biochar.jpg)

Figure 3 illustrates the conceptual hierarchical pore architecture targeted in the porous bio-composite brick.

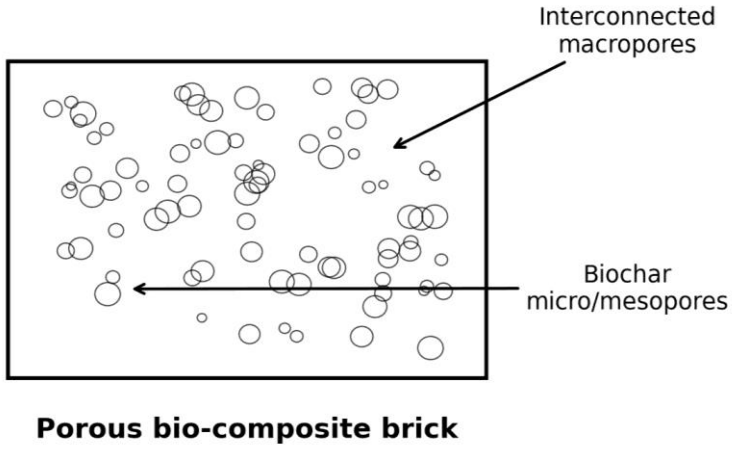

Figure 3. Conceptual hierarchical pore architecture of the porous bio-composite brick. (Source: Zhang, Ran, Haoxiang Wang, Jie Ji, and Hainian Wang, "SEM images of biochar and graphite," Wikimedia Commons, CC BY 4.0. https://commons.wikimedia.org/wiki/File:SEM_images_of_biochar_and_graphite.png)

Figure 4 provides the reference image for the Portland-cement component listed in Table 2.

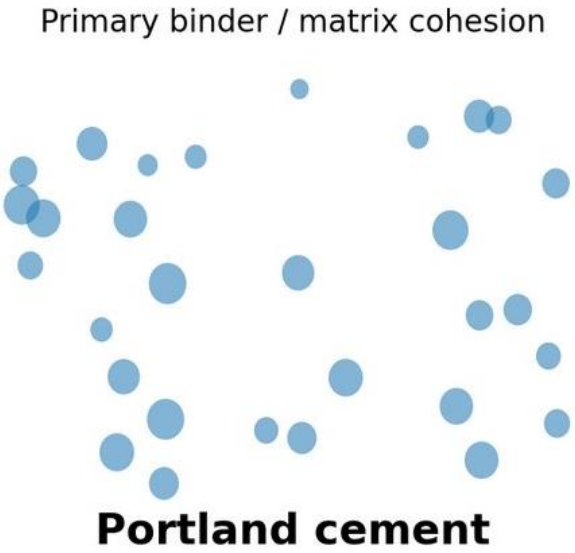

Figure 4. Portland cement (Source: Achim Hering, "Firestopmortar.jpg," Wikimedia Commons, CC BY 3.0. https://commons.wikimedia.org/wiki/File:Firestopmortar.jpg)

Figure 5 provides the reference image for the zeolite component listed in Table 2.

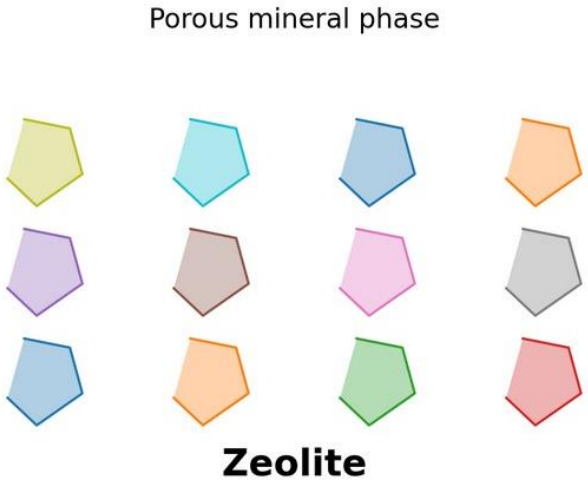

Figure 5. Zeolite (Source: Zihao Rei Gao, "Zeolite.png," Wikimedia Commons, CC BY 4.0. https://commons.wikimedia.org/wiki/File:Zeolite.png)

Figure 6 provides the reference image for the natural-fiber reinforcement listed in Table 2.

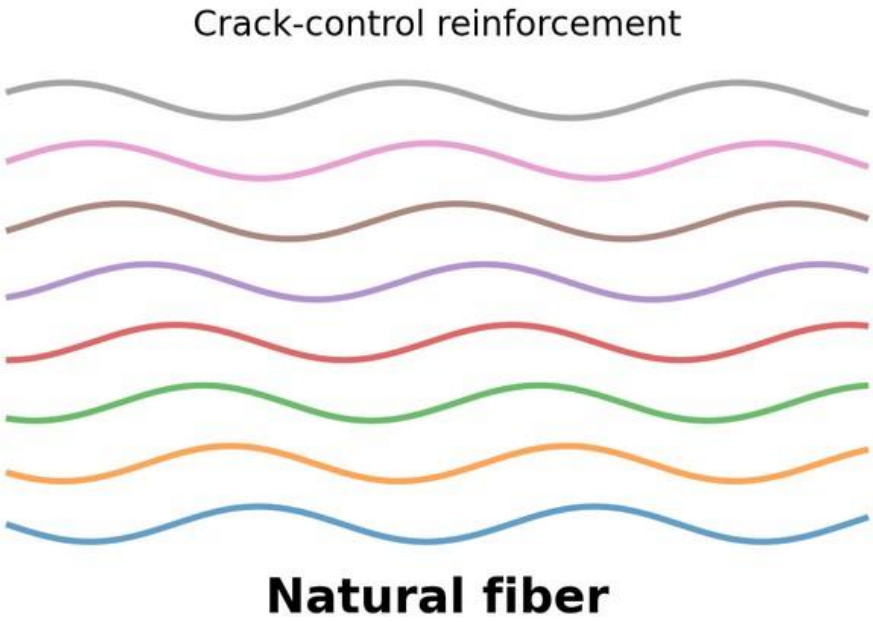

Figure 6. Natural fiber **(**Source: W. Zhang, "Scanning electron microscope (SEM) micrograph of a lyocell rayon fiber," Wikimedia Commons, CC BY 3.0. https://commons.wikimedia.org/wiki/File:Scanning_electron_microscope_(SEM)_micrograph_of_a_lyocell_rayon_fiber.png)

Figure 7 provides the reference image for the standardized mold used conceptually for specimen fabrication.

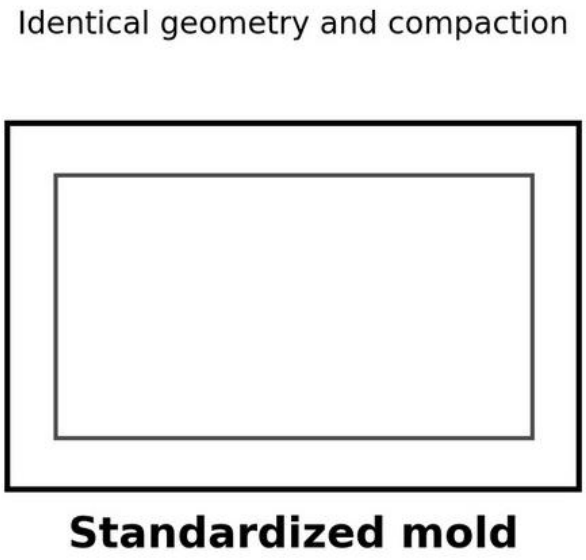

Figure 7. Standardized mold (Source: Metropolitan Museum of Art, "Brick mold MET 25.3.108 top.jpg," Wikimedia Commons, CC0. https://commons.wikimedia.org/wiki/File:Brick_mold_MET_25.3.108_top.jpg)

Figure 8 presents the controlled chamber architecture used as the basis for PM2.5 evaluation.

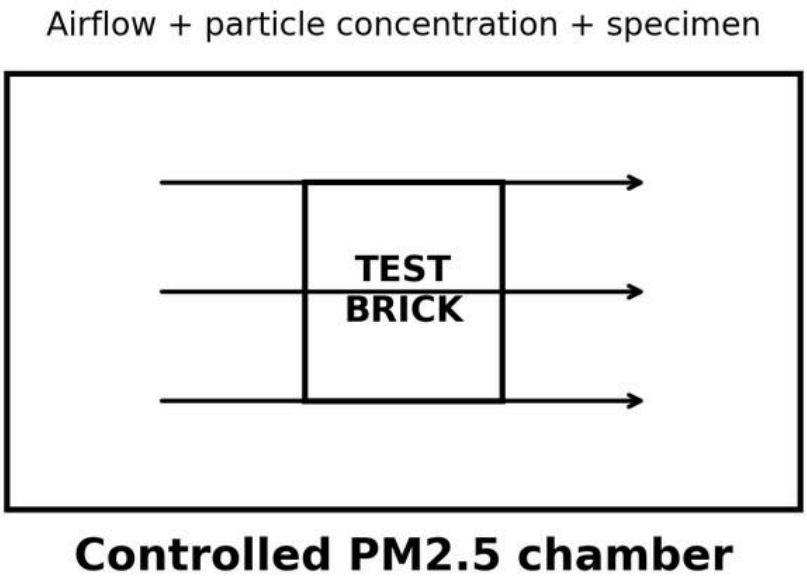

Figure 8. Controlled PM2.5 test chamber (Source: D. Papoutsakis et al., "A Review of Low-Cost Particulate Matter Sensors from the Developers' Perspectives," Sensors, 2020, Fig. 11 (aerosol chamber schematic). https://www.mdpi.com/1424-8220/20/23/6819)

11. PROPOSED EXPERIMENTAL DESIGN

11.1 Formulations

Biochar loading will be defined on a dry-mass basis relative to the selected solid mixture. The 0-20 wt% window is an experimental range, not a predetermined optimum. Zeolite, heme-based additive, fiber loading, water protocol, specimen geometry, and compaction procedure will remain fixed unless a separate experiment explicitly investigates them. The formulation levels are summarized in Table 3.

Table 3. Proposed biochar-loading formulations.

Code	Biochar loading	Purpose
C0	0 wt%	Non-biochar control
B1	5 wt%	Low-biochar formulation
B2	10 wt%	Intermediate formulation
B3	15 wt%	High formulation
B4	20 wt%	Upper-bound formulation

11.2 Preparation of Durian Peel Biochar

- Wash and mechanically clean the durian peel to remove soil and adhering residues.
- Dry the material to constant mass and record initial and final mass to quantify moisture loss.
- Reduce the dried peel to a relatively uniform feed size.
- Perform oxygen-limited pyrolysis using suitable laboratory equipment under supervised conditions. Record peak temperature, residence time, heating rate, and atmosphere.
- Allow the char to cool under controlled conditions before exposure to ambient air.
- Mill and classify the char into predefined particle-size fractions.
- Store each batch in a sealed, dry container and record a batch identification code.

11.3 Brick Fabrication Procedure

- Dry-weigh all solid constituents according to the experimental formulation.
- Dry-blend cement, zeolite, biochar, fiber, and the heme-based additive until visually uniform.
- Add water gradually using a fixed mixing protocol and record the total water mass.
- Place the mixture into identical molds using the same filling mass and compaction procedure.
- Apply standardized compaction energy; avoid uncontrolled over-vibration that could collapse or redistribute the pore network.
- Demold after sufficient green strength has developed.
- Cure all specimens under identical temperature and humidity conditions for predetermined intervals, preferably 7 and 28 days for preliminary comparison.
- Condition specimens using a consistent protocol before physical, mechanical, and PM2.5 testing.

12. CHARACTERIZATION AND MEASUREMENTS

The planned characterization measurements and their purposes are summarized in Table 4

Table 4. Planned characterization measurements and purposes.

Property	Measurement approach	Purpose
Bulk density	Mass / external volume	Assess material compactness
Open porosity	Validated laboratory porosity method	Quantify accessible void volume
Water absorption	Mass change after controlled immersion	Indirect indicator of accessible pore structure
Compressive strength	Universal testing machine / compression tester	Evaluate structural integrity
Surface morphology	Optical microscopy; SEM if available	Observe pore architecture
Surface chemistry	FTIR if available	Identify major surface functional groups
PM2.5 removal	Calibrated particle monitor in controlled chamber	Quantify particulate reduction

12.1 Advanced Characterization

Where facilities permit, scanning electron microscopy (SEM) can be used to visualize pore morphology, BET N_2 adsorption-desorption can quantify specific surface area and pore-size distribution of the biochar, and FTIR can characterize major surface functional groups. These analyses strengthen the link between microstructure, surface chemistry, and observed PM2.5 performance. If advanced instruments are unavailable at school level, measurements may be conducted through a qualified university laboratory with instrument model, calibration status, and uncertainty reported where available.

13. CONTROLLED PM2.5 EVALUATION

A closed-loop or controlled-flow test chamber will be used so that the same specimen geometry, airflow rate, exposure time, and starting particle concentration are applied to every formulation. A blank run without a specimen will quantify particle decay caused by settling or leakage. A conventional non-functional brick may also be tested to distinguish passive deposition from material-specific effects.

- Record timestamp, PM2.5 concentration, temperature, relative humidity, airflow rate, specimen mass, specimen dimensions, and test condition.
- Use at least three independent specimens per formulation for preliminary statistical comparison.
- Measure PM2.5 concentration at defined time intervals to obtain concentration-time curves rather than relying only on a single endpoint.
- Repeat the blank and control runs sufficiently to assess chamber stability and measurement repeatability.

13.1 Removal Efficiency

At a defined time point, apparent removal efficiency can be calculated as:

$$\text{Removal efficiency (\%)} = [(C_o - C_t) / C_o] \times 100$$

Where C_o is the initial PM2.5 concentration and C_t is the concentration at the selected exposure time. Because concentration can decline even without a specimen, blank-corrected analysis should also be considered. Time-series curves, normalized removal rates, and area-under-the-curve comparisons can provide more robust evidence than a single endpoint.

14. DATA ANALYSIS AND STATISTICAL PLAN

- Report replicate measurements as mean±standard deviation and provide confidence intervals where the sample size permits.
- Check distributional assumptions before applying parametric tests; use appropriate non-parametric alternatives when assumptions are not satisfied.
- Compare formulations using effect sizes in addition to p-values so that practical magnitude is considered alongside statistical significance.
- Evaluate relationships among biochar loading, open porosity, density, water absorption, strength, and PM2.5 removal using correlation or regression where appropriate.
- Use a predefined multi-objective decision matrix to rank candidate formulations before viewing the final outcome, reducing the risk of selecting a formulation after seeing the data.

14.1 Decision Criteria

The decision logic to be applied after data collection is summarized in Table 5.

Table 5. Predefined multi-objective decision criteria

Criterion	Decision logic	Reason
Accessible porosity	Higher than or meaningfully improved relative to control	Supports air transport through the material
PM2.5 reduction	Statistically supported reduction under identical conditions	Demonstrates material-specific performance
Compressive strength	Acceptable for intended non-load-bearing application	Prevents environmental function from being achieved at the expense of structural integrity
Reproducibility	Consistent performance across independent specimens	Improves scientific defensibility
Overall score	Best balance across all criteria	Avoids single-metric optimization

15. EXPECTED RESULTS AND DISCUSSION

Because the source project is a research proposal and experimental results have not yet been generated, this section presents testable expectations rather than fabricated numerical findings. The central expectation is that biochar loading will produce measurable changes in pore structure and material performance, and the study will test whether intermediate formulations differ from the zero-biochar control and the highest-loading formulation when PM2.5 removal, accessible porosity, and compressive strength are considered together.

At low biochar loading, the material may retain comparatively strong matrix cohesion but provide fewer carbonaceous interaction sites. As loading increases, additional porous carbon may improve accessible surface and pollutant interaction; however, excessive fine biochar may occupy pore throats, increase heterogeneity, or weaken the cementitious matrix. Consequently, the relationship between biochar loading and PM2.5 removal is expected to be non-linear and should be established from measured data.

The strongest scientific outcome will therefore not necessarily be the formulation with the largest single PM2.5 reduction. A more defensible result would be a formulation that demonstrates reproducible particulate reduction while retaining adequate open porosity and compressive strength. This interpretation directly follows the project's multi-objective design and the reported pore-blockage concern in high-biochar permeable materials [7].

If SEM, BET, or FTIR data are obtained, these results can be used to explain whether differences in performance are associated with pore morphology, specific surface area, or surface functional groups. Such structure-property evidence would substantially strengthen the mechanistic interpretation.

16. ENVIRONMENTAL IMPACT AND SUSTAINABILITY

- Agricultural-waste valorization: durian peel is converted from a disposal burden into a functional carbon precursor.
- Material integration: the project explores a passive environmental function within a construction-material platform.
- Resource efficiency: using a locally available biomass residue may reduce dependence on virgin carbonaceous adsorbents, subject to future life-cycle and cost assessment.
- Research-to-application pathway: the final formulation can be evaluated later for non-load-bearing blocks, panels, or architectural surfaces after durability, weathering, regeneration, fouling, and standards testing.

17. SAFETY AND ENVIRONMENTAL CONSIDERATIONS

- Pyrolysis must be performed only with suitable laboratory equipment, ventilation, supervision, and documented risk controls.
- Fine biochar is a combustible particulate material; dust generation should be minimized and laboratory housekeeping and respiratory protection should follow institutional guidance.
- Cement powder can irritate the skin and respiratory tract; appropriate PPE and dust controls are required.
- The heme-based additive must be handled according to its verified chemical identity, safety data sheet (SDS), and laboratory risk assessment.
- PM2.5 generation for testing must use an approved laboratory method and controlled chamber. People should not be intentionally exposed to elevated particulate concentrations.
- The prototype is an experimental material and should not be represented as a certified air-cleaning device without independent validation.

18. LIMITATIONS

- Controlled-chamber PM2.5 removal does not automatically represent outdoor field performance.
- Optical particle sensors may respond to particle composition and humidity; calibration and instrument limitations must be documented.
- Very high biochar loading may cause pore blockage and loss of mechanical integrity.
- The chemical identity and function of the heme-based additive must be experimentally verified rather than inferred from its name.
- Long-term durability, regeneration, weathering, fouling, and life-cycle performance require follow-up studies.

19. WORK PLAN

The planned activities and deliverables are summarized in Table 6.

Table 6. Research work plan and deliverables

Weeks	Activity	Deliverable
1-2	Literature review; finalize variables and risk assessment	Research protocol
3-4	Durian peel preparation and biochar production	Biochar batches
5-6	Particle classification and material characterization	Material dataset
7-8	Brick formulation and molding	Prototype specimens
9-10	Curing and physical/mechanical characterization	Property dataset
11-12	Controlled PM2.5 chamber validation	Air-quality dataset
13-14	Replicate experiments and statistical analysis	Validated comparison
15-16	Optimization, discussion, report and presentation	Final research package

20. INNOVATION AND EXPECTED CONTRIBUTION

- Hierarchical pore engineering: links bulk pore connectivity with biochar-scale porosity.
- Multi-objective optimization: evaluates particulate removal together with mechanical integrity and accessible porosity.
- Material–process–property linkage: treats pyrolysis conditions, particle size, loading, pore structure, and performance as connected variables.
- Local waste valorization: transforms durian peel into a higher-value environmental material.
- Scalable concept: provides a research pathway toward non-load-bearing blocks, architectural panels, or passive environmental surfaces after appropriate validation.

21. CONCLUSION

This study proposes a scientifically testable route for developing porous bio-composite bricks from durian-peel-derived biochar for PM2.5 interaction. The research is designed around a central engineering principle: useful porosity is not simply the total amount of empty space, but the accessible and interconnected pore network that can support airflow while retaining structural integrity. By combining controlled biochar loading, porous mineral and functional additives, standardized fabrication, physical and mechanical characterization, and controlled PM2.5 testing, the project can evaluate the relationship among biochar loading, pore structure, mechanical properties, and particulate-removal performance on the basis of measurable evidence rather than assumptions. The project also has a clear environmental contribution through agricultural-waste valorization. Most importantly, the final claim will be determined by experimental validation. No numerical performance result should be reported as established until the proposed tests have been completed with appropriate controls and replication.

22. REFERENCES

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