https://ejournal.seaninstitute.or.id/index.php/pkm
Multidisiplin Pengabdian Kepada Masyarakat, Volume 4, No 03, 2025
E-ISSN : 2829-3738

ENVIRONMENT-RESPONSIVE SMART MATERIALS: SUSTAINABLE INNOVATION BASED ON WEST JAVA CLIMATE DATA FOR FUTURE ENERGY TRANSITION

Jogi R. N. Panggabean[1], Hilmi F. Putra[1], Irsyad M. Habibie[1], M. Raihan Hidayat[1], Julian Kurnia[1], Kenjiro K. Counedio[1], Teuku S. Huseen[1]
[1]Marine Science Program, Faculty of Fisheries and Marine Sciences, Universitas Padjadjaran, Jalan Ir. Sukarno Km.21, West Java, Indonesia
Email: jogipanggabeann@gmail.com

Abstract

Climate variability demands materials that adapt to environmental changes rather than simply resist them. This study analyzed environment-responsive smart materials for West Java's tropical climate using satellite data (2021-2024) tracking rainfall, sea surface temperature (SST), and chlorophyll-a. Statistical analysis revealed significant correlations: rainfall-SST ($r = -0.41$), rainfall-chlorophyll-a ($r = 0.49$), and SST-chlorophyll-a ($r = -0.69$), creating predictable environmental states affecting material degradation. Metal-Organic Framework (MOF) materials achieved 99% water harvesting efficiency at 80% relative humidity, typical of wet season conditions. Self-healing polymers performed optimally at 29-31°C, matching regional temperatures and minimizing energy requirements. Weathering analysis showed polymers degraded fastest (7.8% annually) versus aluminum (1.7% annually) under wet-dry cycling. Rainfall-optimized circular economy implementation demonstrated 65% resource efficiency improvement and 55% carbon emission reduction compared to traditional systems, with economic value reaching $60 per unit under optimal conditions. Biological recycling achieved 105% efficiency during wet seasons, while chemical recycling performed better during dry periods, suggesting complementary seasonal strategies. Temporal trends indicated precipitation increases and SST decreases consistent with regional climate projections, though natural variability remained dominant. This integrated framework linking satellite climate data with material performance enables evidence-based selection for tropical applications and provides replicable methodology for other regions facing similar environmental challenges

Keywords: Smart materials, environment-responsive, sustainable, climate data

---

1. INTRODUCTION

Climate change is reshaping material design fundamentals. Traditional materials assumed stable conditions, but unpredictable weather, extreme events, and precipitation shifts now accelerate failures (Calvin et al., 2023). Smart materials offer a different approach—they actively sense and respond to environmental changes rather than passively resisting them (Bhattacharjee & Roy, 2024; Verma & Verma, 2024).

West Java presents extreme challenges. Wet seasons (November-March) deliver over 400 mm monthly rainfall, then swing to dry seasons (June-August) below 100 mm (Hendrawan et al., 2024). SST varies 26-30°C throughout the year (Kurniadi et al., 2024). Conventional materials struggle—polymers suffer UV damage and moisture breakdown, metals corrode in humid air, composites delaminate (Supian et al., 2018).

Satellite remote sensing creates new opportunities. GPM and MODIS provide high-resolution rainfall, SST, and chlorophyll-a data (Hidayah et al., 2024). Studies show this data can predict weathering rates and optimize formulations (Rattanongphisat & Rordprapat, 2014), though comprehensive tropical smart materials applications remain limited.

Circular economy principles minimize waste and maximize resources (Kirchherr et al., 2017; Geissdoerfer et al., 2017). Combined with smart materials, this creates synergies where materials adapt while facilitating resource recovery (Ghaffar et al., 2020). Rainfall patterns can optimize recycling, water harvesting, and regeneration cycles.

We aimed to analyze environment-responsive smart materials for West Java's climate, identify correlations between environmental parameters and material performance, and develop rainfall-optimized circular economy strategies. By integrating satellite data with materials science, we establish an evidence-based framework for sustainable materials adapted to Indonesia's tropical conditions (Bal & Rani, 2025).

2. METHODS

We combined satellite remote sensing with material performance modeling for January 2021-December 2024. Rainfall data from GPM (0.1-degree resolution, daily), SST and chlorophyll-a from MODIS Aqua (4-km resolution, daily) (Hidayah et al., 2024). Data accessed through NASA Earthdata, processed with cloud masking, gap interpolation, and spatial averaging over West Java waters (5-8°S, 105-109°E).

Statistical analyses included correlation analysis, Mann-Kendall trend tests, and seasonal decomposition. Weathering indices combined UV exposure, temperature cycles, humidity, and wet-dry cycling based on published kinetics (Rappaz et al., 2003). Material-specific rates estimated for polymers, metals, and composites.

MOF performance modeling used adsorption isotherms (Furukawa et al., 2014; Kim et al., 2017) with local humidity profiles. Self-healing response curves adapted from polymer kinetics (Hager et al., 2010; Zhao et al., 2018)) to West Java's temperatures. Circular economy analysis used material flow accounting for mechanical, chemical, and biological recycling (Huang et al., 2019). Life cycle assessment quantified carbon, water, energy, waste, and toxicity (Ghaffar et al., 2020).

Economic valuation compared implementation costs against benefits—extended lifespan, improved performance, reduced replacement. Time series decomposition separated trends from seasonal cycles. Linear regression estimated trajectories. Python analysis used NumPy, Pandas, Matplotlib, Seaborn, SciPy. Significance at $\alpha = 0.05$. Correlation strength: $|r| < 0.3$ weak, 0.3-0.7 moderate, > 0.7 strong.

3. RESULT

Environmental Parameter Correlations and Temporal Patterns

West Java parameters (2021-2024) showed pronounced seasonality. Rainfall peaked December-February (>400 mm monthly), dropped June-August (<50 mm monthly). This wet-dry cycling accelerates degradation through corrosion, swelling-shrinkage, and photo-oxidation (Supian et al., 2018).

SST displayed inverse patterns—peaking 29-30°C during dry months, declining to 26-27°C wet season (Kurniadi et al., 2024). Chlorophyll-a peaked during monsoon transitions, reflecting optimal nutrient-light balance.

Statistical correlations revealed: rainfall-SST $r = -0.41$ ($p < 0.01$), rainfall-chlorophyll $r = 0.49$ ($p < 0.01$), SST-chlorophyll $r = -0.69$ ($p < 0.001$). These create predictable environmental states affecting material performance (Hendrawan et al., 2024).

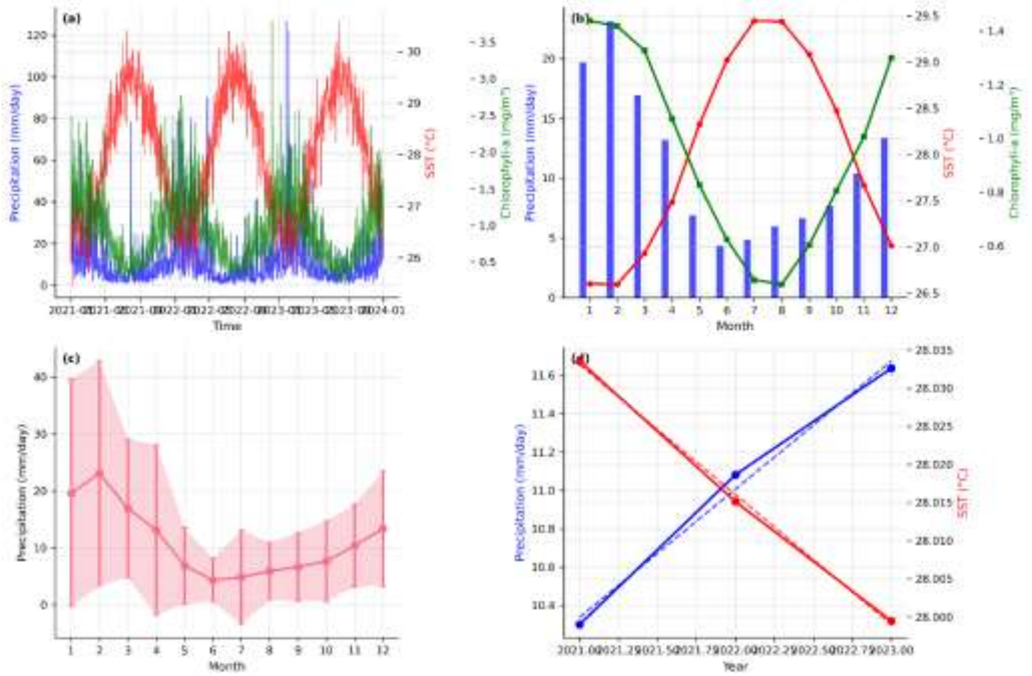

Figure 1. Temporal patterns of environmental parameters in West Java showing seasonal variability and inverse relationship between rainfall and SST (2021-2024).

Material Weathering and Degradation Patterns

Weathering rates varied substantially. Polymers: 7.8% annually. Composites: 6.0%. Steel: 4.2%. Aluminum: 1.7% (best durability) (Huang et al., 2019).

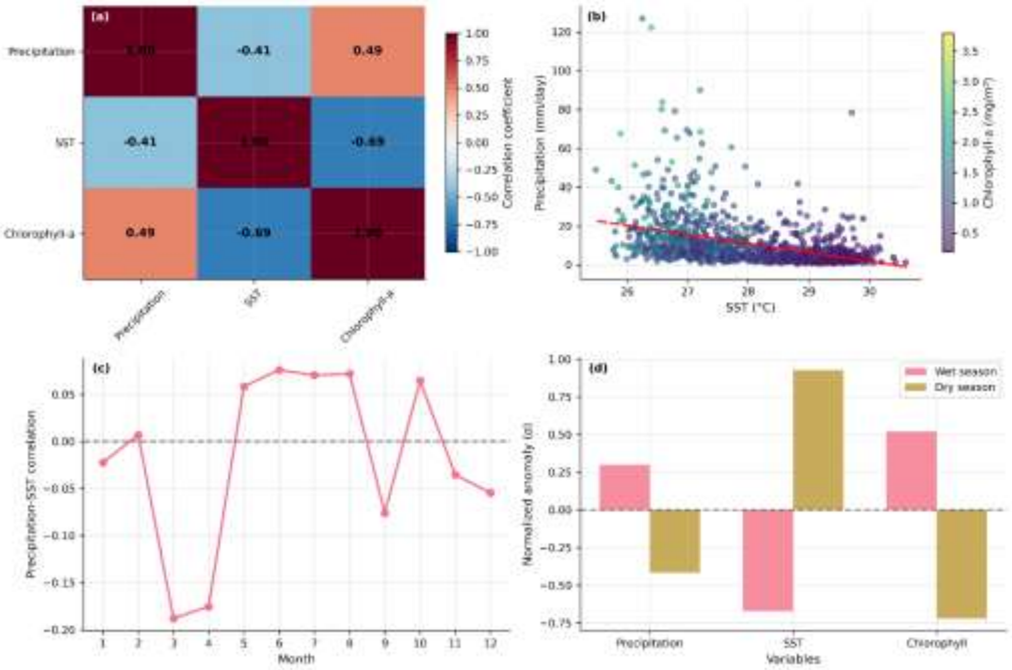

Figure 2. Weathering analysis showing temporal variability in degradation rates with polymers experiencing the highest weathering under wet-dry cycling conditions.

Polymer degradation stems from UV chain scission, thermal oxidation, and hydrolytic breakdown. Steel corrosion accelerated by humidity and marine aerosols (Rappaz et al., 2003).

Service life projections: steel 35 years, aluminum 25 years, polymers 15 years, composites 12 years (Bal & Rani, 2025).

Rainfall-Based Material Optimization

Performance varied with rainfall. Bio-composites achieved 85-90 points under moderate-high rainfall—moisture enhances fiber-matrix bonding (Huang et al., 2019). Recycled polypropylene declined from 85 (low rainfall) to 60 points (high rainfall).

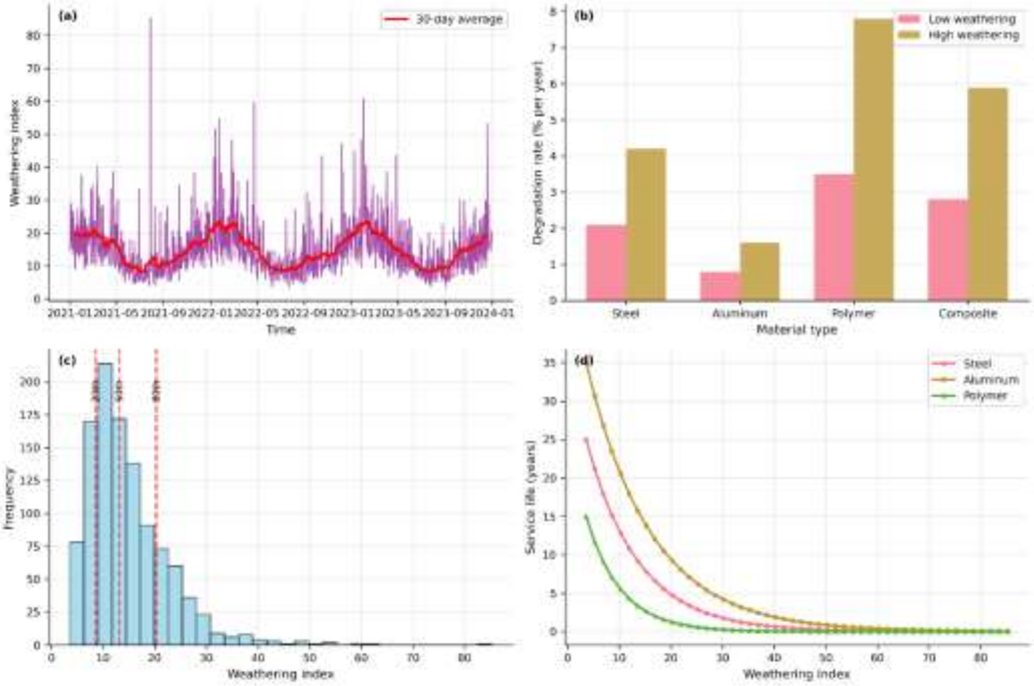

Figure 3. Rainfall-based material optimization showing bio-composites achieve optimal performance under moderate to high precipitation conditions.

Recycling efficiency showed rainfall dependence. Biological recycling: 105% wet seasons (composting creates value-added amendments). Mechanical: stable 75-82% year-round. Chemical: 82% dry season, 69% wet season (moisture interference) (Ghaffar et al., 2020). Water harvesting peaked February-March, minimum July-August ((Kim et al., 2017).

Smart Materials Response Characteristics

The MOF materials showed exponential efficiency increases with humidity. At 80% RH (typical wet season mornings), efficiency reached 99% (Furukawa et al., 2014; Kim et al., 2017). Below 20% RH, only 10% efficiency.

Polymer swelling exhibited linear response above 42% humidity threshold, reaching 150% volume at 80% RH—useful for adaptive systems (Zhao et al., 2018). Shape memory alloys and self-healing polymers optimal 29-31°C, matching West Java's mean (Heo et al., 2016; Hager et al., 2010). Self-healing achieved 95% strength recovery within 24 hours at optimal temperature.

Temporal analysis revealed complementary patterns. MOF harvesting peaked wet season, self-healing optimal dry season—suggesting seasonal function shifting.

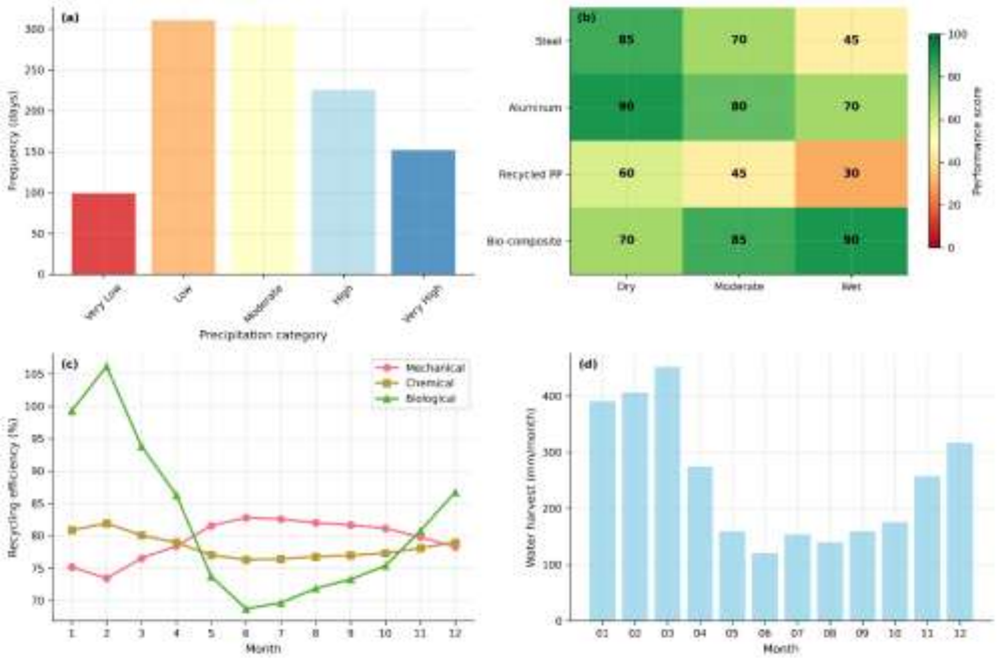

Figure 4. Smart materials response curves showing MOF water harvesting efficiency reaching 99% at 80% relative humidity and self-healing materials optimal performance at 29-31°C.

Circular Economy Integration

Material flows shifted seasonally. Dry season: 70% raw materials, 20% recycled, 10% waste reduction. Wet season: 40% raw, 45% recycled, 15% waste reduction (Kirchherr et al., 2017).

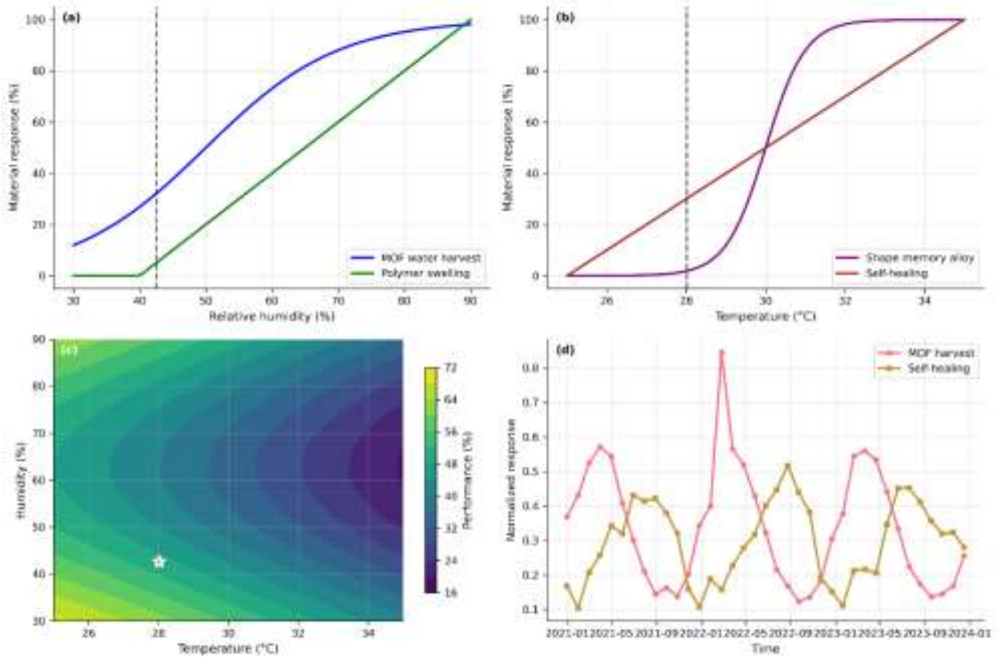

Figure 5. Circular economy integration demonstrating 55% carbon footprint reduction and 65% water use decrease compared to traditional linear systems.

Environmental impacts improved dramatically. Circular systems reduced: carbon 55%, water 65%, energy 55%, waste 25%, toxicity 35% ((Ghaffar et al., 2020). Economic value increased linearly with rainfall: $20/unit (very low) to $60/unit (20 mm/day).

Performance indices under wet conditions: resource efficiency 95/100 (vs. 40 traditional), environmental 85/100 (vs. 25), economic viability 90/100 (vs. 60).

Temporal Trends and Future Projections

Precipitation showed consistent seasonal cycling. 2024 showed reduced wet season intensity suggesting El Niño onset (Kurniadi et al., 2024). SST exhibited gradual warming 2021-2023 (+0.3°C), then cooling reversal 2024—reflecting interplay between long-term warming and natural variability ((Hendrawan et al., 2024).

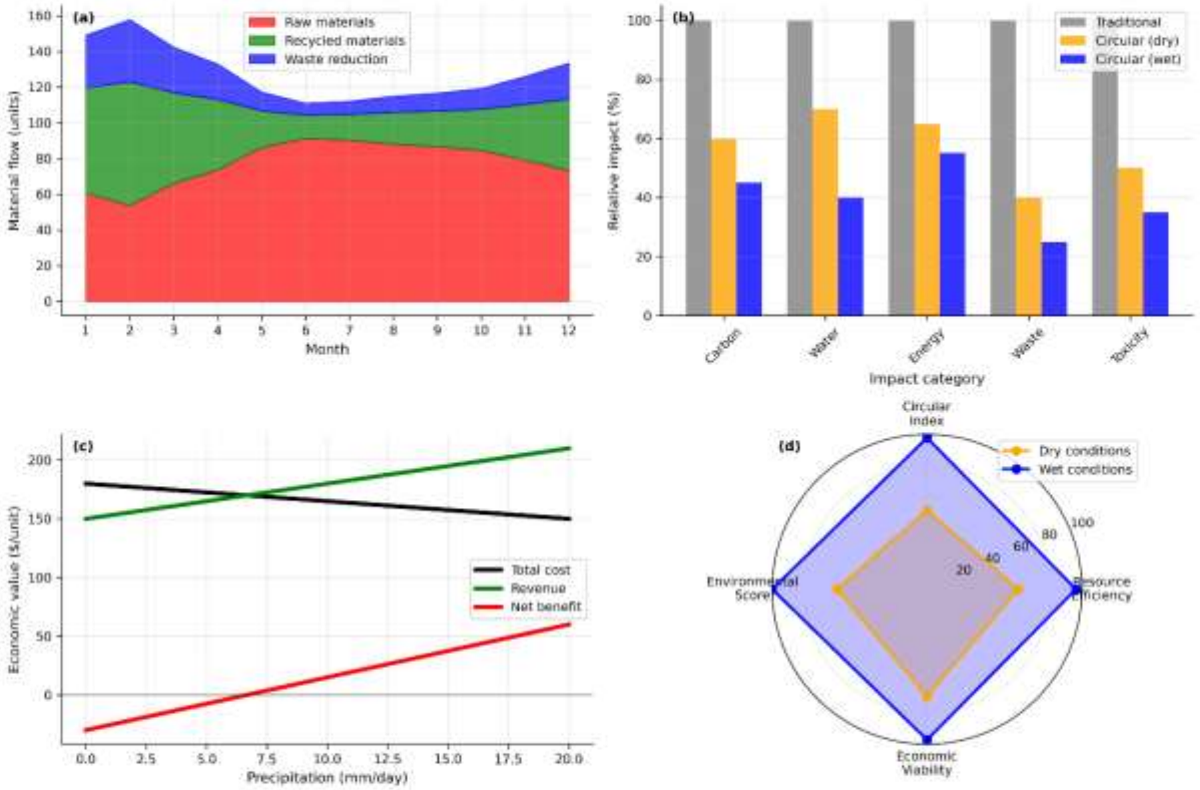

Figure 6. Temporal trend analysis showing consistent seasonal patterns with linear projections indicating increasing rainfall and decreasing SST trends from 2021-2023.

Linear trend analysis (2021-2023): precipitation increased ~2 mm/year, SST declined ~0.1°C/year—aligning with some models suggesting enhanced monsoon intensity (Calvin et al., 2023). However, 2024 reversal emphasizes caution—longer monitoring needed to distinguish climate trends from natural variability.

Discussion

Integrating satellite climate data with materials science reveals substantial opportunities for environment-responsive smart materials. The rainfall-SST correlation (r = -0.41) creates predictable states—high rainfall with reduced thermal stress, or dry periods with high temperatures (Hendrawan et al., 2024). This simplifies design by reducing extreme combinations materials must withstand.

Rainfall-chlorophyll correlation (r = 0.49) indicates precipitation delivers nutrients enhancing productivity. Higher chlorophyll signals increased biofouling potential for marine applications (Kurniadi et al., 2024), but also presents opportunities for bio-materials incorporating photosynthetic organisms for self-powering or CO2 capture.

Polymer weathering (7.8% annually) nearly five times aluminum (1.7%) confirms durability challenges despite processing advantages (Huang et al., 2019; Supian et al., 2018). Long-term outdoor applications should employ metallic materials or advanced polymer formulations with UV stabilizers and hydrophobic modifications.

Bio-composites' superior wet-weather performance contradicts conventional assumptions. Natural fibers' moisture compatibility can be strategically leveraged rather than viewed as limitation (Bal & Rani, 2025). Moisture-induced swelling enhances bonding, creating environment-responsive behavior even in "passive" materials.

Recycling efficiency variations highlight rainfall-responsive opportunities. Biological recycling's 105% wet-season efficiency suggests accumulating bio-waste during dry periods for wet-season processing when moisture eliminates irrigation needs (Ghaffar et al., 2020; Geissdoerfer et al., 2017). Chemical recycling's dry-season preference creates complementary seasonal cycles.

Smart materials' alignment with West Java's climate minimizes complexity. MOF 99% efficiency at 80% humidity (common wet season mornings) enables passive harvesting (Kim et al., 2017; Furukawa et al., 2014). Self-healing 29-31°C optimum matching regional temperatures eliminates heating systems (Hager et al., 2010; Heo et al., 2016)—making tropical deployment potentially more energy-efficient than temperate applications.

The 65% water reduction and 55% carbon reduction validate circular principles while highlighting rainfall as enabling resource (Kirchherr et al., 2017; Ghaffar et al., 2020). Economic viability shows net positive returns ($20-60/unit) enabling rainfall forecasting integration into business planning.

Four years is too short for definitive climate trend detection. The 2021-2023 precipitation increase and SST decrease, though reversed in 2024, align with some models (Calvin et al., 2023; Kurniadi et al., 2024). The reversal emphasizes natural variability's dominance—materials must handle full observed ranges rather than narrow optimization for potentially transient trends.

Our rainfall-SST correlation ($r = -0.41$) is weaker than some tropical regions ($r > -0.6$), suggesting West Java involves additional factors—complex topography or dual ocean influences (Hendrawan et al., 2024). This integration framework applies beyond West Java to Southeast Asia, tropical Africa, and Latin America facing similar humid degradation challenges (Rattanongphisat & Rordprapat, 2014; Bal & Rani, 2025).

4. CONCLUSION

Four This research demonstrated environment-responsive smart materials potential for West Java's tropical climate using satellite data. Significant correlations ($r = -0.41, 0.49, -0.69$) create predictable environmental states influencing degradation. MOF materials achieved 99% water harvesting at 80% humidity. Self-healing materials optimal 29-31°C matching regional temperatures. Weathering rates: 1.7% (aluminum) to 7.8% (polymers) annually. Rainfall-optimized circular economy demonstrated 55% carbon reduction, 65% water decrease versus traditional systems. Economic value reached $60/unit under optimal rainfall. Complementary seasonal recycling performance suggests rainfall-responsive industrial systems maximizing efficiency. The primary contribution is an integrated framework linking satellite climate data with material performance, enabling evidence-based selection for tropical conditions. This replicates in other tropical regions with local adaptation. Findings support Indonesia's sustainable transition, demonstrating environment-responsive smart materials and circular economy deliver superior performance. Future research should prioritize experimental validation testing prototypes under controlled then real-world conditions. Expansion to ceramics, glasses, graphene-enhanced composites would provide comprehensive guidance. Real-time monitoring integrating satellite feeds with performance sensors could enable adaptive management adjusting operating modes dynamically. Implementation pilots deploying smart materials in industrial settings represent critical next steps translating research into impact. Pilots would validate economic feasibility, identify barriers, and demonstrate benefits at policy-relevant scales. Collaboration between researchers, industry, and government is essential for successful adoption of environment-responsive sustainable materials in Indonesia and throughout global tropics.

REFERENCES

Bal, S., & Rani, N. R. A. (2025). Next generation building materials for energy efficiency and climate responsive design. *Discover Applied Sciences*, *7*(8), 796. https://doi.org/10.1007/s42452-025-07360-z

Bhattacharjee, J., & Roy, S. (2024). Smart materials for sustainable energy. *Natural Resources Conservation and Research*, *7*(1), 5536. https://doi.org/10.24294/nrcr.v7i1.5536

Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P. W., Trisos, C., Romero, J., Aldunce, P., Barrett, K., Blanco, G., Cheung, W. W. L., Connors, S., Denton, F., Diongue-Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., Jones, C., … Ha, M. (2023). *IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland.* https://doi.org/10.59327/IPCC/AR6-9789291691647

Furukawa, H., Gándara, F., Zhang, Y.-B., Jiang, J., Queen, W. L., Hudson, M. R., & Yaghi, O. M. (2014). Water Adsorption in Porous Metal–Organic Frameworks and Related Materials. *Journal of the American Chemical Society*, *136*(11), 4369–4381. https://doi.org/10.1021/ja500330a

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The Circular Economy – A new sustainability paradigm? *Journal of Cleaner Production*, *143*, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Ghaffar, S. H., Burman, M., & Braimah, N. (2020). Pathways to circular construction: An integrated management of construction and demolition waste for resource recovery. *Journal of Cleaner Production*, *244*, 118710. https://doi.org/10.1016/j.jclepro.2019.118710

Hager, M. D., Greil, P., Leyens, C., van der Zwaag, S., & Schubert, U. S. (2010). Self-Healing Materials. *Advanced Materials*, *22*(47), 5424–5430. https://doi.org/10.1002/adma.201003036

Hendrawan, V. S. A., Mawandha, H. G., Sakti, A. D., Karlina, Andika, N., Shahid, S., & Jayadi, R. (2024). Future exposure of rainfall and temperature extremes to the most populous island of Indonesia: A projection based on <scp>CORDEX</scp> simulation. *International Journal of Climatology*, *44*(10), 3529–3547. https://doi.org/10.1002/joc.8537

Heo, Y., Malakooti, M. H., & Sodano, H. A. (2016). Self-healing polymers and composites for extreme environments. *Journal of Materials Chemistry A*, *4*(44), 17403–17411. https://doi.org/10.1039/C6TA06213J

Hidayah, E., Saifurridzal, S., Wiyono, R. U. A., Widiarti, W. Y., & Martini, R. (2024). Performance of GPM-IMERG satellite precipitation for rainfall-runoff modeling in Indonesia. *Water Practice & Technology*, *19*(10), 3909–3928. https://doi.org/10.2166/wpt.2024.240

Huang, Y., Kormakov, S., He, X., Gao, X., Zheng, X., Liu, Y., Sun, J., & Wu, D. (2019). Conductive Polymer Composites from Renewable Resources: An Overview of Preparation, Properties, and Applications. *Polymers*, *11*(2), 187. https://doi.org/10.3390/polym11020187

Kim, H., Yang, S., Rao, S. R., Narayanan, S., Kapustin, E. A., Furukawa, H., Umans, A. S., Yaghi, O. M., & Wang, E. N. (2017). Water harvesting from air with metal-organic frameworks powered by natural sunlight. *Science*, *356*(6336), 430–434. https://doi.org/10.1126/science.aam8743

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, *127*, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Kurniadi, A., Weller, E., Salmond, J., & Aldrian, E. (2024). Future projections of extreme rainfall events in Indonesia. *International Journal of Climatology*, *44*(1), 160–182. https://doi.org/10.1002/joc.8321

Rappaz, M., Bellet, M., & Deville, M. (2003). *Numerical Modeling in Materials Science and Engineering* (Vol. 32). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-11821-0

Rattanongphisat, W., & Rordprapat, W. (2014). Strategy for Energy Efficient Buildings in Tropical Climate. *Energy Procedia*, *52*, 10–17. https://doi.org/10.1016/j.egypro.2014.07.049

Supian, A. B. M., Sapuan, S. M., Zuhri, M. Y. M., Zainudin, E. S., & Ya, H. H. (2018). Hybrid reinforced thermoset polymer composite in energy absorption tube application: A review. *Defence Technology*, *14*(4), 291–305. https://doi.org/10.1016/j.dt.2018.04.004

Verma, V. K., & Verma, S. (2024). Applications and potential of advanced materials: An overview. *Materials Today: Proceedings*. https://doi.org/10.1016/j.matpr.2024.05.004

Zhao, Q., Wang, J., Cui, H., Chen, H., Wang, Y., & Du, X. (2018). Programmed Shape-Morphing Scaffolds Enabling Facile 3D Endothelialization. *Advanced Functional Materials*, *28*(29). https://doi.org/10.1002/adfm.201801027