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Development of a Circular Economy Framework for Coffee Grounds Recycling: From Pyrolysis-based Activated Carbon to Service Platform Integration

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The rapid growth of Taiwan's coffee market has led to the generation of more than 10000 tons of spent coffee grounds (SCGs) annually, which are typically incinerated or landfilled, resulting in significant carbon emissions. In this study, we developed and validated a circular economy framework for coffee grounds valorization, integrating waste collection, drying, pyrolysis, and activated carbon (AC) production with a digital reverse logistics platform. A compact in-store dryer was designed and tested, achieving a consistent removal of >20 g of water per 100 g of grounds within 15 min at 105–185 ℃. Grounds samples were sieved to ≤150 μm prior to pyrolysis. Batch pyrolysis trials (20–500 g, 500–750 ℃) demonstrated stable carbonization yields above 40% under optimized conditions (500 g at 500 ℃, 60 min, ~43% yield). The resulting AC met industrial quality standards, exhibiting surface areas of 630–680 m^2/g, iodine concentrations of 690–730 mg/g, and methylene blue adsorption capacities of 150–180 mg/g. Application tests confirmed >96% chlorine removal efficiency in water filtration. A web-based service platform was simultaneously developed to record, analyze, and manage collection and recycling data across pilot 7-Eleven stores, enabling traceability and integration into existing logistics systems. Economic projections indicate a potential value creation of NT$1.5M in the first year, increasing to NT$45M by the third year. The findings demonstrate the feasibility of coupling biomass-derived AC production with digital service flows to reduce waste disposal burdens and establish replicable circular business models within large retail ecosystems.

1. Introduction

Coffee is one of the most widely consumed beverages globally and represents a major agricultural commodity, generating large volumes of solid residues throughout its supply chain.

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A considerable proportion of this waste arises during consumption as spent coffee grounds (SCGs), which are discarded in cafés, offices, households, and retail outlets. Recent estimates suggest that between 6 and 8 million tons of SCGs are produced annually worldwide, with waste intensities particularly high in instant coffee production where approximately 2 kg of wet SCGs is generated per kilogram of powder.[1–3] The conventional management of SCGs typically involves landfilling or incineration, practices that release carbon dioxide directly or generate methane through anaerobic degradation when landfilled. These routes not only accelerate greenhouse gas emissions but also represent a missed opportunity for resource recovery, especially since SCGs streams are compositionally consistent and relatively free of contaminants compared with mixed food waste.[1,4]

From a compositional standpoint, SCGs are a lignocellulosic biomass rich in polysaccharides, lignin, proteins, lipids, and phenolic compounds, with an immediate moisture content of approximately 50–70 wt% after brewing.[4–6] This biochemical profile enables several valorization pathways. Lipids may be extracted to produce biodiesel precursors, while caffeine and phenolics can serve the food, cosmetic, and nutraceutical industries.[5,6] The carbon-rich residue lends itself to thermochemical upgrading such as pyrolysis, gasification, or activation to produce biochar and activated carbon (AC). Compared with other heterogeneous biomass wastes, the stable composition of SCGs facilitates process reproducibility and product standardization.[4]

Over the past decade, studies have progressed from exploring single-purpose uses of SCGs, such as direct combustion or pelletization, to considering integrated biorefinery concepts in which multiple fractions (lipids, phenolics, carbohydrates, and solids) are valorized in parallel.[1,5,6] Additional applications include the incorporation of SCGs into polymer composites, building materials, and ceramic supports, although durability and leachate risks remain challenges.[5,6] Among these routes, the production of AC has gained prominence because of the high fixed-carbon yield and tunable pore structure that can be achieved.[7–12] Depending on activation protocols, physical (CO_2 or steam) or chemical (KOH, H_3PO_4, $ZnCl_2$), reported Brunauer-Emmett-Teller (BET) surface areas for SCGs-derived AC range from 400 to more than 1000 m^2 g^{-1}, with iodine numbers and dye uptake capacities comparable to or exceeding those of commercial carbons.[7–11]

AC is widely applied in environmental remediation and water treatment, including the removal of organic micropollutants, disinfection by-product precursors, and taste-and-odor compounds. In drinking water treatment specifically, AC plays a critical role in polishing free chlorine residuals after disinfection, as chlorine is often detectable at concentrations below health-based limits and is undesirable from an organoleptic perspective.[12–14] This demand positions SCGs-derived AC as a renewable alternative to coal-based carbons, although comparative life cycle assessments (LCAs) continue to show that impacts depend heavily on drying, activation conditions, and transport logistics.[12,15,16]

Despite a growing body of laboratory research, most studies remain confined to material synthesis and characterization under controlled conditions. System-level implementation issues such as decentralized drying to address high moisture contents; reverse logistics to collect widely dispersed SCGs; traceability; environmental, social, and governance (ESG) reporting for corporate partners; and techno-economic assessments are comparatively underexplored.[1,15–17] Recent advances in Industry-4.0-enabled platforms suggest that digital systems can help coordinate collection, pretreatment, and processing, while generating transparent datasets suitable for compliance and stakeholder reporting.[16,17] Against this backdrop, in this study, we developed a circular economy framework that combines (i) the in-store drying of SCGs, (ii) the pyrolysis-based production of AC with rigorous performance benchmarking, and (iii) a web-based reverse logistics platform that integrates collection, processing, and product distribution. The objective is to demonstrate a replicable model that unites materials engineering with digital system integration, thereby contributing to both waste valorization and sustainable retail operations.

2. Data, Materials, and Methods

2.1 Raw materials and collection framework

SCGs were obtained from five 7-Eleven convenience stores in Tainan, Taiwan, through a pilot reverse logistics program established in collaboration with retail partners. Each store was equipped with a dedicated collection bin to prevent cross-contamination with other waste materials. Collected SCGs were stored at 4 °C and transported to the laboratory within 48 h.

The average initial moisture content of fresh SCGs was determined gravimetrically by oven-drying at 105 °C to a constant weight and was found to be 60–65 wt%. This high moisture content posed both storage and transport challenges, motivating the development of a decentralized drying system.

2.2 In-store drying system

A compact dryer was designed and fabricated for in-store use (dimensions: 25 × 30 × 42 cm; maximum heating capacity: 1200 W; power supply: 110 V) (Fig. 1). The dryer chamber was fitted with a forced-air circulation system to ensure uniform heating. Drying tests were conducted using 100 g batches of fresh SCGs at two temperatures (105 and 185 °C) and a fixed residence time of 15 min (Table 1).

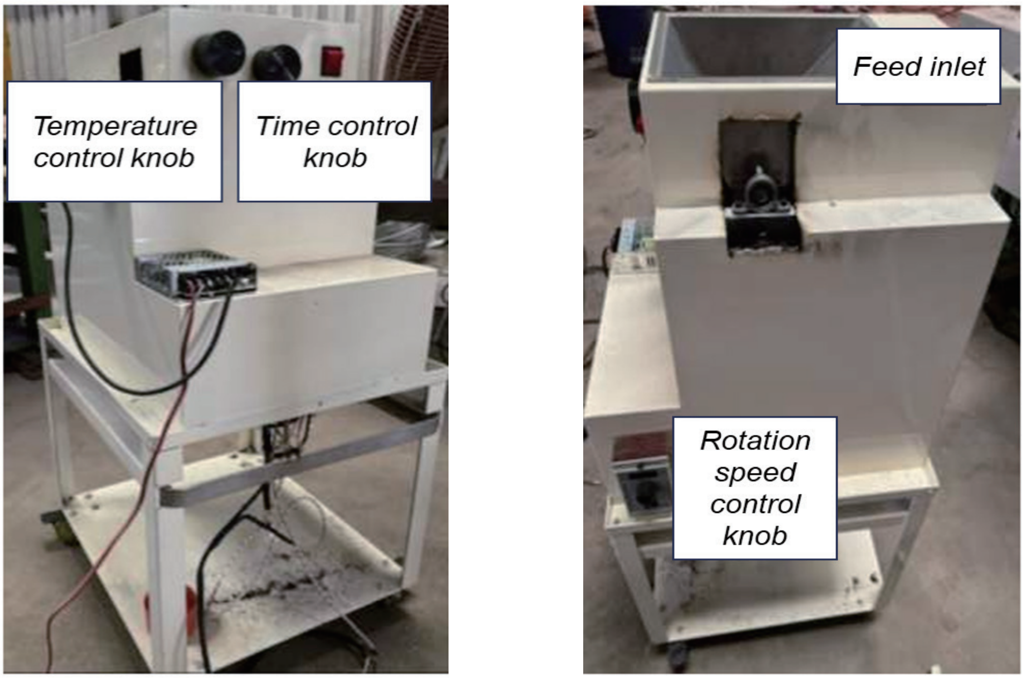
Moisture removal (*MR*, %) was calculated as

$$MR = \frac{W_i - W_f}{w_i} \times 100, \tag{1}$$

where W_i is the initial wet weight (g) and W_f is the final dried weight (g).

2.3 Grinding and sieving

After drying, SCGs were homogenized using a laboratory mill (IKA MF10, Germany) at 3000 rpm. The ground material was sieved through a vibratory sieve shaker (Retsch AS200)



(a) (b)

Fig. 1. (Color online) Photographs of the in-store drying system. (a) Front view showing temperature and time control knobs. (b) Top view showing feed inlet and rotation speed control knob.

Table 1
Moisture removal of SCGs under two drying conditions.

Temperature (°C)	Time (min)	Initial mass (g)	Final mass (g)	Moisture removed (g)	*MR* (%)
105	15	100.068	76.937	23.131	23.12
105	15	100.043	73.211	26.832	26.82
105	15	100.034	77.491	22.543	22.54
105	15	100.099	71.449	28.65	28.62
105	15	100.036	74.281	25.755	25.75
185	15	100.129	63.361	36.768	36.72
185	15	100.149	64.088	36.061	36.00
185	15	100.013	66.875	33.138	33.13

with mesh sizes ranging from 30 to 140 mesh. The target acceptance criterion was particle size ≤150 μm (100 mesh), ensuring uniformity for subsequent pyrolysis and activation. Particle size distribution was determined by laser diffraction analysis (Malvern Mastersizer 3000).

2.4 Pyrolysis procedure

Thermochemical conversion was performed in a horizontal tubular furnace (Carbolite Gero, UK) under a continuous nitrogen flow (200 mL/min) to maintain an inert atmosphere. Experimental parameters included (1) temperature: 500, 600, and 750 °C; (2) residence time: 60, 70, and 90 min; (3) batch size: 20, 100, and 500 g; and (4) heating rate: maintained at 10 °C/min to the target temperature.

Carbonization yield (CY, %) was calculated as

$$CY = \frac{M_c}{M_0} \times 100\,, \tag{2}$$

where M_c is the mass of the carbonized product (g) and M_0 is the initial dry mass (g).

2.5 AC activation and characterization

2.5.1 Activation

The carbonized SCGs were activated physically under CO_2 flow at 850 °C for 2 h. A secondary set of samples was chemically activated with KOH (weight ratio 1:3, SCGs:KOH) followed by heating at 700 °C for 1 h, washed with 1 M HCl, and rinsed to neutral pH.

2.5.2. Characterization

- Proximate analysis: ASTM D3173–3175 (moisture and ash)
- BET surface area: N_2 adsorption–desorption at −196 °C (Micromeritics ASAP 2020)
- Pore size distribution: BJH method
- Iodine number: ASTM D4607-94
- Methylene blue adsorption: batch test with 100 mg/L MB solution
- pH: slurry method (1 g AC in 100 mL distilled water)

2.6 Water filtration tests

To evaluate functional performance, AC was packed into polypropylene filter cartridges (1000 g each). Tap water was passed through the cartridges at a continuous flow (0.1 L/min) for 5 min. The residual chlorine concentration C_f was measured by the DPD colorimetric method (Hach DR3900).

Removal efficiency (RE, %) was calculated as

$$RE = \frac{C_i - C_f}{C_i} \times 100\,, \tag{3}$$

where C_i is the initial chlorine concentration (mg/L). Triplicate tests were performed.

2.7 Digital service platform

A cloud-based logistics management platform was developed using Google Apps Script as the back end and HTML5/CSS/JavaScript as the front end. The platform architecture comprised four modules, as shown in Fig. 2: (1) collection management: store-level data entry for SCG

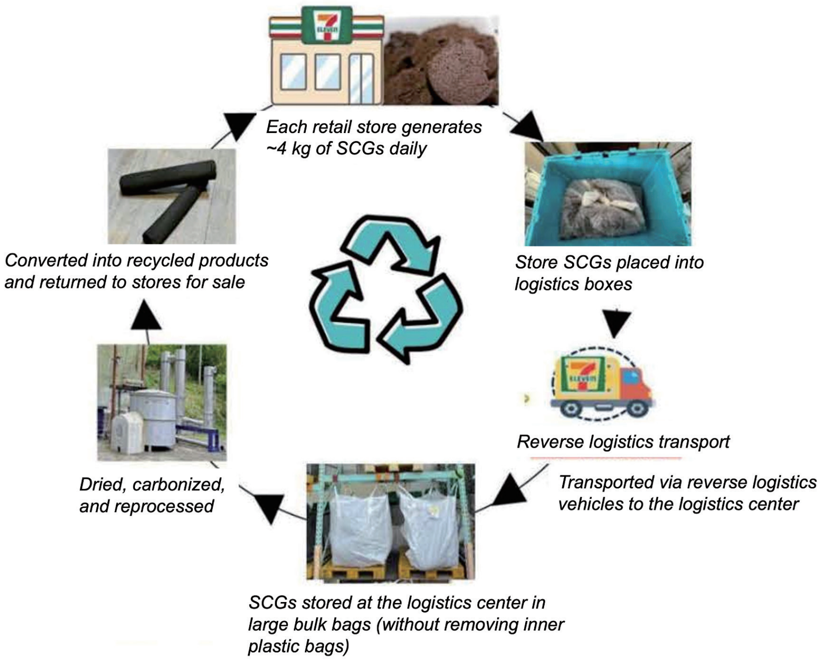


Fig. 2. (Color online) System architecture of the digital reverse logistics platform.

weight and time, (2) transport management: integration with logistics routes of retail partners, (3) processing management: carbonization and activation batch recording, and (4) analytics: automated report generation for material flows, yields, and ESG compliance.

The platform was tested in five pilot stores. Each functional module was subjected to ten trial runs to verify accuracy and consistency.

3. Results and Discussion

3.1 Drying performance and implications for reverse logistics

The compact in-store dryer achieved average moisture removals of 26.8% at 105 °C and 36.7% at 185 °C for 100 g SCGs batches processed over 15 min (Table 1). These results are consistent with reported drying rates of lignocellulosic biomass under convective heating[15], confirming that decentralized pretreatment can substantially reduce the water burden associated with SCG logistics. Reducing moisture from ~65 to ~30–40 wt% lowers transported mass by 25–35%, which directly affects energy consumption and logistics costs. Such decentralized drying is particularly relevant in convenience store chains, where large numbers of small SCG streams are generated daily.

3.2 Particle size distribution

Grinding and sieving yielded a consistent particle size ≤150 μm, with laser diffraction showing that >90% of the mass fraction fell between 50 and 150 μm. This uniformity is critical for pyrolysis, as smaller particle sizes enhance devolatilization kinetics, promote pore development, and improve the reproducibility of AC characteristics.[4] The result aligns with prior studies that reported optimum particle size ranges of 75–150 µm for SCGs thermochemical upgrading.[8]

3.3 Pyrolysis yield optimization

CY decreased as pyrolysis temperature increased, with values ranging from 42–45% at 500 °C to 31% at 750 °C (Table 2). These trends reflect enhanced secondary cracking reactions and increased volatile evolution at higher temperatures, consistent with lignocellulosic thermochemical behavior.[6] Our optimized condition, 500 °C for 60 min with 500 g batches, achieved reproducible yields of ~43%, surpassing prior SCGs studies that typically report 32–36% at 600 °C.[8,9] This suggests that lower pyrolysis temperatures can balance yield and porosity development, providing favorable carbon efficiency without excessive energy input.

3.4 AC properties

The SCGs-derived AC exhibited BET surface areas of 630–680 m²/g, iodine numbers of 690–730 mg/g, and methylene blue adsorption capacities of 150–180 mg/g (Table 3). Chemical activation with KOH produced slightly higher BET surface areas (~680 m²/g) than physical CO_2 activation (~650 m²/g), reflecting the stronger pore development capacity of alkali reagents. All properties met industrial specifications (≥500 m²/g BET, ≥600 mg/g iodine number, ≤20% ash).[18]

These values are comparable to those of commercial carbons derived from coal (typically 600–1200 m²/g BET, 600–1000 mg/g iodine number)[19] and confirm that SCGs-derived AC is suitable for water treatment applications. Notably, the MB adsorption capacity (~165 mg/g) was similar to those reported for SCG-based carbons activated at 700–800 °C with KOH.[7]

3.5 Water filtration performance

Filter cartridges containing 1000 g of SCGs-derived AC removed >96% of free chlorine from the initial concentration at 0.52 mg/L. Residual concentrations decreased below 0.02 mg/L after

Table 2
*CY*s under different pyrolysis conditions.

Batch size (g)	Temperature (°C)	Time (min)	Yield (%)
20	500	70	40.6
20	600	70	36.5
100	750	90	31.1
500	500	60	42.7
500	500	60	43.2
500	500	60	45
500	500	60	43.6
500	500	60	44.7

Table 3
SCGs-derived AC samples with standard specifications.

Parameter	This study (*mean* ± *SD*)	Standard acceptance range	Compliance
BET surface area (m^2/g)	650 ± 20	≥500 (500–1300) m^2/g	✓
Iodine number (mg/g)	710 ± 15	≥600 (600–1200) mg/g	✓
MB adsorption (mg/g)	165 ± 10	≥120 mg/g	✓
Ash content (%)	16 ± 1	≤20%	✓
Moisture (%)	0.1	≤10%	✓
pH	5.6 ± 0.1	>5 (5–10)	✓
Pore size distribution	≥120 mesh	>200 mesh (74 μm)	✓

5 min, a performance level comparable to that of commercial AC filters (85–95% chlorine removal under equivalent conditions).[13] This suggests that the porosity and surface chemistry of SCGs-derived AC are suitable for domestic water purification, especially in polishing chlorine and organoleptic compounds. Longer-term column experiments would be required to assess breakthrough curves and capacity under continuous flow, but the initial tests indicate high application potential.

3.6 Digital platform validation

The data collected from five pilot stores showed that the interval between SCG recovery and dryer input varied between 3 and 7 h, depending on store operations. Statistical comparisons revealed that controlling storage time to ≤8 h minimized fermentation-related variability and moisture fluctuations, thereby improving both drying stability and subsequent carbonization consistency.

Drying operations were standardized by company directive to a 100 g batch size, with processing time capped at 25 min. Under these conditions, the pyrolysis *CY* stabilized at ~45%, with the most consistent yields (45–48%) being obtained when drying was completed within 20–25 min. Variance analysis confirmed that the fluctuations of *CY* were smallest in this time window, underscoring its suitability as a standardized operational parameter.

On the basis of these insights, the research team proposed a three-shift operation model in which SCGs are collected and cleared at least once daily, dried within 8 h of recovery, and logged into the platform with timestamps for recovery time, drying start, and drying end. This digitalized SOP ensures both operational reproducibility at the store level and centralized oversight across the logistics network. Importantly, it demonstrates how digital platforms can move beyond passive traceability to active process optimization, validating the role of data-driven analytics in standardizing decentralized biomass valorization systems. Moreover, the digital service platform provides a structured data chain that can directly support ESG reporting and Scope 3 waste-reduction documentation, aligning with frameworks such as ISO 14064-2 and BS 8001.

3.7 Comparative analysis

Our results confirm that SCGs-derived AC can achieve adsorption properties comparable to those of commercial carbons while offering additional sustainability advantages. Prior LCAs suggest that SCGs valorization into AC can reduce greenhouse gas emissions by ~30–40% compared with landfill disposal and by 20–25% relative to incineration.[3,17] Importantly, the integration of digital logistics ensures that environmental benefits are traceable, verifiable, and scalable across multiple retail outlets.

3.8 Carbon emissions analysis: transport–drying trade-off

To examine whether decentralized drying contributes net carbon benefits, we analyzed the balance between transport emissions saved and dryer electricity emissions. For 1 ton of wet SCGs (65 wt% moisture), drying removed 26.8–36.7% of mass. Transport savings were estimated using a freight emission factor of 0.062 kg CO_2 per ton-kilometer (t-km), consistent with IPCC/IEA guidelines for heavy-duty trucks.[20] Dryer emissions were calculated from the measured energy intensity of the small dryer (3.0 kWh/kg wet SCGs) and Taiwan's grid emission factor (0.495 kg CO_2/kWh in 2022).[21]

At a 100 km one-way transport distance, drying reduced transport emissions by only 1.7–2.3 kg CO_2 per ton, while dryer emissions were ~1500 kg CO_2 per ton processed. Even assuming improved dryer efficiencies to industrial-scale dewatering (0.3 ± 0.02 kWh/kg wet SCGs), breakeven distances required to offset drying emissions were on the order of 6000–90000 km one way, far exceeding realistic logistics routes. Thus, in-store drying powered by Taiwan's grid electricity is not carbon-beneficial when evaluated solely for transport mass reduction.

The analysis emphasis is that the primary environmental benefit of SCG valorization lies in avoided disposal (methane from landfills, auxiliary fuel use in incineration) and product substitution (coal-based AC replacement), rather than moisture-related logistics savings. Decentralized drying can still be advantageous if powered by low-carbon electricity such as rooftop solar panels at convenience stores, which would reduce $CO_{2\ \mathrm{dryer}}$ substantially.

This quantitative analysis highlights the importance of aligning pretreatment technology with energy sources. Without renewable integration, the dryer itself becomes the dominant emission source, negating transport savings. Future work should therefore model full life cycle inventories including pyrolysis, activation, and substitution benefits to provide a comprehensive carbon balance.

4. Conclusions

In this study, we developed and validated an integrated circular economy framework for the valorization of SCGs into AC filter materials, coupled with a digital logistics and service platform. The major findings can be summarized as follows.

(1) Decentralized pretreatment: A compact in-store dryer reduced SCG moisture by 26.8–36.7% within 15–25 min for 100 g batches. Platform-recorded data indicated that maintaining SCG storage times within ≤8 h and drying within 25 min stabilized pyrolysis yields, with optimal performance (45–48%) achieved in the 20–25 min range.

(2) Pyrolysis and activation: Under optimized conditions (500 °C, 60 min, 500 g batch), *CY*s of ~43% were obtained, exceeding reported values for SCGs in comparable studies. Both CO_2-

and KOH-AC met industrial standards, with BET surface areas of 630–680 m^2/g, iodine numbers of 690–730 mg/g, and methylene blue adsorption of 150–180 mg/g.

(3) Application performance: Water filtration tests confirmed >90% chlorine removal, demonstrating parity with commercial AC cartridges. This validates SCGs-derived AC as a viable, renewable alternative for household and industrial purification applications.

(4) Digital platform integration: Beyond traceability, the platform enabled the statistical analysis of process parameters, revealing the critical influence of storage and drying times on yield stability. These insights guided the development of standardized SOPs across stores, demonstrating how data-driven feedback loops can enhance reproducibility in decentralized biomass valorization.

(5) Carbon footprint implications: Quantitative analysis showed that in-store drying powered by Taiwan's grid electricity (0.502 kg CO_2/kWh) increased emissions relative to transport savings, with breakeven distances of >20000 km. This highlights that the dominant environmental benefit arises from avoided disposal emissions and the substitution of coal-based AC, rather than logistics optimization. Integration with renewable energy is essential to realize net reductions in operational carbon intensity.

5. Future Work

Several research directions are necessary to consolidate and extend this work. A comprehensive LCA should be conducted to quantify the full environmental implications of SCG valorization, including avoided landfill or incineration emissions, the displacement of fossil-derived AC, and the comparative performance of renewable versus grid-powered drying and activation systems. Scaling up to a larger network of convenience stores will be important to evaluate the robustness of the service platform, the consistency of SCGs supply, and the practicality of SOPs across diverse operational settings. At the same time, research on low-carbon drying technologies such as mechanical dewatering, solar-assisted drying, and integration with waste-heat sources can reduce energy intensities from the measured 3.0 kWh/kg wet SCGs to below 0.5 kWh/kg, thereby making decentralized drying both economically and environmentally favorable.

In parallel, the long-term performance of SCGs-derived AC must be investigated through continuous-flow filtration experiments, breakthrough curve analysis, and regeneration studies. Such investigations will confirm their durability and reusability in real-world applications, where multicomponent contaminants and fluctuating water qualities are encountered. The digital service platform can also evolve beyond traceability to a predictive and adaptive system by incorporating IoT-enabled sensors at the store level to automatically monitor moisture, temperature, and batch weights. This will reduce operator workload, enable real-time analytics, and allow the adaptive optimization of drying and carbonization parameters across the network. Finally, the conceptual framework demonstrated here can be extended to other high-moisture, compositionally stable residues such as tea waste and brewery spent grains, thereby broadening the scope of waste-to-resource pathways and reinforcing the integration of materials engineering with digital supply chain management in urban circular economies.

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