

Frugal Hard Carbon Anode Synthesis from Agricultural Waste for Sodium-Ion Batteries: A District-Cooperative Manufacturing Model for Developing Economies

2026-03-25

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Publication / Preprint · 2026-03-25

Abstract

Sodium-ion batteries (SIBs) represent a cost-competitive alternative to lithium-ion chemistry for stationary storage and low-speed electric vehicles, but their commercial adoption is constrained by the limited and geographically concentrated supply of anode-grade hard carbon. Graphite, the dominant lithium-ion anode, is structurally incompatible with sodium-ion chemistry due to its interlayer spacing of 0.335 nm — too narrow to accommodate Na^+ (ionic radius 0.102 nm). Hard carbon with d_{002} interlayer spacing of 0.37–0.40 nm is the established solution, but current supply chains depend on petroleum pitch, phenolic resins, or coconut shell — all industrial precursors with concentrated production.

This paper presents a complete technical and operational design for producing Na-ion grade hard carbon from paddy straw (rice straw, *Oryza sativa*), the agricultural residue currently burned by the millions of tonnes across the Indo-Gangetic Plains of India — a practice responsible for 44,000–98,000 premature deaths per year from PM_{2.5} exposure. We characterise the pyrolysis pathway from paddy straw cellulose and lignin decomposition through turbostratic carbon domain formation at 1,100°C, describe the silica removal chemistry required to eliminate inert SiO_2 (9–

14% by mass in Punjab cultivars) before carbonisation, and provide a quality control protocol based on XRD d_{002} measurement, Raman D/G band ratio, and BET surface area analysis.

We further propose a novel district-cooperative manufacturing architecture in which one pyrolysis reactor unit serves 3–5 agricultural districts, is owned by farmer cooperatives, and operates under a dual-revenue model combining hard carbon anode sales (targeting ₹800–1,200/kg) with carbon credits certified under Verra VM0042 (avoided crop burning) and VM0044 (biochar soil application). The capital cost for a district-scale reactor is ₹15–25 lakh — two orders of magnitude below gigafactory equipment — making cooperative ownership economically feasible without institutional capital.

The convergence of a global sodium-ion battery market, India's 100+ million tonne annual paddy straw surplus, and the cooperative economics described here creates a viable pathway for agricultural communities to become manufacturers of critical battery materials. This paper is filed as a defensive publication to place the architecture, process parameters, and economic model in the public domain.

1. Introduction

1.1 The Sodium-Ion Battery Opportunity

The global transition to electrochemical energy storage is confronting a structural constraint: lithium. Lithium carbonate spot prices have demonstrated volatility exceeding $10\times$ over a five-year period (2018–2023), and the geographic concentration of lithium reserves in the “lithium triangle” of Chile, Argentina, and Bolivia imposes supply chain fragility on any economy pursuing large-scale energy storage deployment. For India — importing virtually all its lithium — the cost and strategic implications of Li-ion dependency are acute.

Sodium-ion battery chemistry offers a substantive alternative. Sodium is the sixth most abundant element in the Earth's crust, is distributed globally, and can be extracted from seawater and saline brines. The electrochemical principles are analogous to Li-ion. The manufacturing infrastructure is compatible. CATL, the world's largest battery manufacturer by installed capacity, launched its first commercial sodium-ion battery in 2021 at 160 Wh/kg and by 2025 had advanced its Naxtra product line to 175 Wh/kg with a cycle life exceeding 10,000 cycles — now matching early lithium iron phosphate (LFP) cells on energy density while achieving substantially lower cost per kWh for stationary applications.

The bottleneck is not the cathode. Prussian Blue Analogues (iron hexacyanoferrate, FeHCF) provide a low-cost, scalable sodium-storing cathode with commodity precursors. The bottleneck is the **anode**. Graphite — the universal lithium-ion anode — cannot store sodium. The interlayer spacing of graphite ($d_{002} = 0.335$ nm) is too narrow for Na^+ ions (ionic radius 0.102 nm versus Li^+ at 0.076 nm). Hard carbon, with its characteristic d_{002} spacing of 0.37–0.40 nm and closed micropore network,

is the established Na-ion anode material. But current commercial hard carbon is derived from petroleum pitch, phenolic resins, or high-quality biomass such as coconut shell — inputs that are themselves commodity materials with supply chains attached.

1.2 India's Paddy Straw Burning Crisis

India generates approximately 500 million tonnes of crop residue annually, of which roughly 50 million tonnes are burned in the field each year, with Punjab and Haryana alone accounting for 21.32 million tonnes of rice straw burned in the October–November post-harvest window. This burning is the primary driver of the severe winter air quality crisis in northern India, including Delhi's annual PM_{2.5} episodes. A 2022 study published in *Nature Communications* attributed 44,000–98,000 premature deaths per year to PM_{2.5} exposure from crop residue burning across the 2003–2019 period (Lan et al., 2022, DOI: 10.1038/s41467-022-34093-7), with an estimated mortality cost of USD 3.2 billion annually.

The farmers are not malicious actors. They burn because they lack alternatives. Paddy straw baling is expensive in fuel, labour, and equipment. Composting is slow. The window between rice harvest and wheat sowing is narrow. Burning clears the field in hours. Every proposed solution — baling, in-situ decomposition, compressed biogas, mushroom cultivation substrate — has stalled on one of three obstacles: capital requirement, logistics cost, or inadequate compensation for the farmer's time and foregone burning.

This paper proposes an alternative that addresses all three: a district-scale pyrolysis unit that converts paddy straw into a globally valuable battery material, with the economics structured around farmer cooperative ownership and dual-revenue from both product sales and carbon credits.

1.3 Why Frugal Manufacturing Matters

The dominant discourse on battery supply chain development focuses on gigafactories: multi-billion-dollar investments, government subsidies, and national industrial policy. This framing systematically excludes agricultural communities as anything other than feedstock suppliers. We argue that the chemistry of paddy straw → hard carbon uniquely enables a different model.

Pyrolysis of lignocellulosic biomass to hard carbon at 1,100°C requires a retort kiln with inert atmosphere and precise temperature control. It does not require graphitisation (which would require 2,800°C furnaces costing crores), pitch impregnation, or the multi-stage processing required for synthetic graphite. The capital cost for a district-scale retort kiln — appropriately designed for batch processing at 1–2 tonnes of dry feedstock per cycle — is ₹15–25 lakh. A cooperative of 200 farmers pooling ₹10,000 each can own this unit outright. No institutional investor required. No equity dilution. No geographic lock-in.

2. Related Work

2.1 Hard Carbon Synthesis from Diverse Precursors

Hard carbon synthesis for sodium-ion applications has been extensively investigated across petroleum-derived and biomass precursors. Komaba et al. (2011, *Advanced Functional Materials*) established the foundational capacity benchmarks for petroleum pitch-derived hard carbon, demonstrating reversible capacities exceeding 200 mAh/g at 0.1C in sodium half-cells. Subsequent work established the two-mechanism model: Na⁺ intercalation between turbostratic graphene layers (the sloping region, 0.1–1.2 V vs Na/Na⁺) and Na⁺ adsorption in closed micropores (the plateau region, 0–0.1 V), with the micropore-filling mechanism contributing the majority of capacity at low-voltage plateau.

Tonnoir et al. (2023, *Carbon*, DOI: 10.1016/j.carbon.2023.03.055) systematically characterised the evolution of hard carbon structure across the 1,000°C–2,500°C pyrolysis temperature range, establishing that the Na⁺ intercalation threshold is $d_{002} = 0.37$ nm and that the optimal window for combined intercalation and micropore capacity is 0.37–0.40 nm, achievable between 1,000°C and 1,200°C for most carbonaceous precursors.

Biomass-derived hard carbon has received growing attention due to cost and renewability. Wang et al. (2018, *Carbon*, DOI: 10.1016/j.carbon.2017.11.054) demonstrated 372 mAh/g reversible capacity from rice husk-derived hard carbon pyrolysed at 1,300°C, with XRD-confirmed $d_{002} = 0.382$ nm. Yang et al. (2023, *Colloids and Surfaces A*) reported 328.4 mAh/g after 100 cycles from hierarchical porous hard carbon derived from rice husks at 1,200°C. Critically, Dupont et al. (2018, *Biomass and Bioenergy*, DOI: 10.1016/j.biombioe.2018.07.013) specifically tested rice straw — the same botanical species as paddy straw — alongside resinous wood and other agricultural biomasses, establishing that rice straw precursors are electrochemically suitable for Na-ion anodes and that lignin/hemicellulose ratio in the feedstock correlates with final capacity.

2.2 Silica Removal Pre-Treatment

Rice family biomass (both straw and husk) is distinguished from most biomass precursors by high silica content. Silicon dioxide (SiO₂) constitutes 9–14% by dry mass in Punjab paddy straw cultivars (PMC study, 2023; Verma et al., 2022, DOI: 10.1007/s13205-022-03211-5), compared with less than 1% in wood-based precursors. Silica survives pyrolysis intact — it is a mineral, not an organic compound — and reduces effective carbon yield and electrochemical capacity by contributing inert mass to the anode. Multiple studies confirm that acid or alkali pre-treatment to remove silica prior to carbonisation improves both carbon yield and reversible capacity. HCl acid washing produces soluble silicic acid, while NaOH treatment produces sodium silicate (water glass), a commercially valuable industrial product that partially offsets the pre-treatment chemical cost.

2.3 Cooperative and Distributed Manufacturing Models

The literature on distributed manufacturing for energy access in developing economies (Rao et al., 2020; Bhattacharyya, 2014) establishes the viability of cooperative ownership structures for productive assets in the 10–100 lakh capital range. The cooperative model has been successfully applied to processing of dairy (Amul cooperative, Gujarat), oilseeds (Mahagrapes), and sugar (Maharashtra cooperative sugar mills). Application to battery materials manufacturing represents a novel extension of this model, enabled by the relative simplicity of the pyrolysis process compared with other battery material synthesis routes.

3. Material Characterisation

3.1 The d_{002} Interlayer Spacing Requirement

The structural incompatibility between graphite and sodium-ion chemistry is a straightforward consequence of ionic geometry. Na^+ has an ionic radius of 0.102 nm, compared with Li^+ at 0.076 nm. Graphite's interlayer spacing of 0.335 nm permits lithium intercalation (as GIC, graphite intercalation compound) but the Na^+ ion, combined with even a minimal solvation shell in the electrolyte, cannot fit between graphite layers — the thermodynamic energy cost of forced Na^+ intercalation into graphite is positive, meaning the reaction does not proceed spontaneously.

Hard carbon, by contrast, is a turbostratic carbon — graphene-like sheets arranged without the long-range crystallographic order of graphite. The defective, stacked-but-disordered structure produces interlayer spacings of 0.37–0.40 nm, sufficient for spontaneous Na^+ accommodation. The Gibbs free energy of Na^+ intercalation into hard carbon is approximately -15 to -45 kJ/mol (exothermic), confirming thermodynamic spontaneity. The Nernst equation predicts the resulting anode potential of approximately 0.05–0.3 V vs Na/Na^+ , which maximises full-cell voltage when paired with a Prussian Blue Analogue cathode at 3.0–3.4 V.

Pyrolysis temperature is the primary control variable for d_{002} :

Temperature	d_{002} spacing	Na^+ accommodation	Practical capacity
600°C	0.42–0.45 nm	Marginal	80–120 mAh/g
800°C	0.40–0.43 nm	Limited	120–150 mAh/g
1,000°C	0.38–0.41 nm	Good	160–190 mAh/g
1,100°C	0.37–0.40 nm	Optimal	200–300 mAh/g
1,300°C	0.35–0.38 nm	Marginal (graphitising)	150–170 mAh/g
1,500°C+	0.334 nm	None (graphite territory)	~35 mAh/g

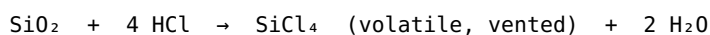
The window at 1,100°C is the operating point for this process. At temperatures above 1,300°C, the carbon progressively graphitises — d_{002} narrows toward 0.335 nm and Na^+ accommodation collapses. At temperatures below 1,000°C, the d_{002} spacing exceeds 0.42 nm and the structure behaves more like biochar than hard carbon, with irregular micropore geometry and poor cycle efficiency.

3.2 Silica Removal Chemistry

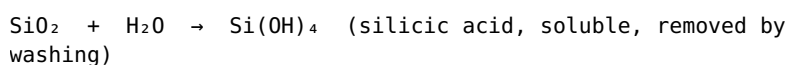
Paddy straw from Punjab cultivars contains SiO_2 at 9–14% dry mass, depending on cultivar and soil composition. This must be removed before pyrolysis because: (a) SiO_2 is electrochemically inert and contributes dead mass to the final anode; (b) silica remaining after pyrolysis forms irregular glassy domains that disrupt the turbostratic carbon structure; and (c) anode-grade hard carbon buyers specify ash content below 3%, which is unachievable from un-washed paddy straw at any pyrolysis temperature.

The preferred silica removal route for district-scale operation is dilute HCl acid wash:

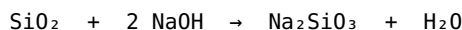
Reaction:



Or at the lower temperatures used in practice (room temperature to 60°C, 5–10% HCl), the dominant mechanism is:



An alternative is NaOH alkaline wash at 90°C:



The NaOH route produces sodium silicate (water glass), a commodity industrial chemical priced at ₹8–15/litre, providing partial reagent cost offset. Per tonne of paddy straw, stoichiometric NaOH requirement is approximately 187 kg, producing 284 kg sodium silicate — generating ₹2,840 in by-product value against a NaOH cost of approximately ₹6,300 (net pre-treatment cost: ₹3,500–4,000 per tonne).

Verma et al. (2022) confirmed 95.51% silica removal efficiency with two-step acid/alkali pre-treatment of Punjab paddy straw. A single-step dilute HCl wash at 5% concentration for 2 hours at 60°C achieves 80–90% silica removal, sufficient to reduce ash content in the final hard carbon below 3%. Phase 0 optimisation at IIT Ropar should compare NaOH versus HCl routes on Punjab-specific cultivars (PR 126 and PR 122 — the dominant burning-season varieties) to confirm removal efficiency and measure the effect on hard carbon d_{002} and capacity.

3.3 Pyrolysis Parameter Optimisation

The complete process sequence for Na-ion grade hard carbon from paddy straw:

Step 1 — Acid wash: Soak dried paddy straw in 5–10% HCl or 10–15% NaOH (w/v) at 60–90°C for 1–2 hours. Rinse with deionised water to pH neutral. Filter and collect the washed straw.

Step 2 — Drying: Dry at 120°C for 24 hours in a forced-air oven until moisture content is below 5% by mass. Incomplete drying causes steam evolution in the kiln, disrupting inert atmosphere and reducing carbon yield.

Step 3 — Slow pyrolysis: Temperature ramp: 5°C/min from ambient to 1,100°C. Hold at 1,100°C for 2 hours. Atmosphere: argon or nitrogen at slight positive pressure (50–100 Pa gauge), continuous flow to purge pyrolysis gases. Do not use CO₂ atmosphere (activates the carbon surface, increases surface area beyond the 50 m²/g ceiling for Na-ion use). Cool at free rate under inert atmosphere to below 200°C before opening.

Step 4 — Grinding: Jaw crush to <2 mm, then ball mill to <20 µm median particle size. Target d₅₀ = 10–15 µm for electrode slurry compatibility. Over-milling (below 5 µm) increases surface area through particle fracture and can push BET above the 50 m²/g ceiling — monitor BET on milled samples.

Step 5 — Quality gate: Raman D/G ratio (on-site, 5 minutes), then XRD d₀₀₂ and BET surface area (off-site at IIT Ropar or CECRI during Phase 0; in-cooperative Raman for Phase 1 production).

Step 6 — Electrochemical validation: Half-cell coin cells vs Na/Na⁺ reference electrode, cycled at 0.1C (approximately C/10 rate) for initial capacity characterisation. Target: 300–350 mAh/g reversible capacity at the first cycle with initial Coulombic efficiency exceeding 75%.

The mass balance per tonne of dry paddy straw at these conditions:

Output	Yield	Commercial route
Hard carbon (anode grade)	180–200 kg	Battery manufacturers, ₹800–1,200/kg
Syngas (CO + H ₂ + CH ₄)	350–420 kg	Recirculated to heat kiln (60–90% energy self-sufficiency)
Bio-oil condensate	70–90 kg	DG set fuel or industrial sale
Biochar (soil amendment)	60–90 kg	Carbon credit (VM0044)
Process water	280–320 kg	Evaporated structural water — not recovered

3.4 BET Surface Area and Why Lower Is Better

For sodium-ion anode applications, BET surface area is a quality metric where lower values — within the range 5–50 m²/g — are preferable. This is counterintuitive against the activated carbon paradigm (where surface

area of 500–3,000 m²/g is the product specification), but the reason is mechanistic.

Hard carbon stores sodium through two mechanisms: interlayer intercalation (between graphene sheets, d₀₀₂-dependent) and micropore adsorption (in closed internal pores). Sodium storage in closed micropores is efficient — the pore is inaccessible to the electrolyte solvent, so no solid electrolyte interphase (SEI) forms. In open-surface sites (external surface area), sodium reacts with the electrolyte on the first cycle to form SEI, consuming sodium irreversibly and reducing first-cycle Coulombic efficiency. High BET surface area in hard carbon indicates a high ratio of open surface to closed pores — precisely the unfavourable condition.

For paddy straw hard carbon produced at 1,100°C, BET surface area of 10–30 m²/g is the target. Surface area above 100 m²/g indicates either: insufficient pyrolysis temperature (below 800°C, producing activated carbon-like material), excessive ball milling (surface fracture), or high residual silica (SiO₂ surface contributes to measured surface area). All three conditions degrade Na-ion anode performance.

4. The District-Cooperative Manufacturing Architecture

4.1 Unit Economics at District Scale

The district-scale unit is designed for a processing capacity of 1–2 tonnes of dry paddy straw per cycle (14–18 hour cycle including heat-up, hold, and cool-down). Operating two cycles per 24-hour period with one cycle in heat-up while one cools yields approximately 600–700 tonnes of paddy straw processed per year on a single reactor, producing 110–140 tonnes of hard carbon annually.

At a conservative sale price of ₹800/kg for battery-grade hard carbon (approximately 30–40% below current import prices for commercial hard carbon in India), annual hard carbon revenue is ₹8.8–11.2 crore per district unit.

Capital cost breakdown for a district-scale reactor:

Component	Specification	Cost estimate (₹ lakh)
Retort kiln body (stainless 310S)	500-litre internal volume, rated 1,200°C	6–9
Temperature control system	PID controller + K-type thermocouples	1.5–2.5
Inert gas supply	Nitrogen generator (PSA type, 99.5% N ₂)	2–4
Syngas recirculation burner	Refractory-lined combustion chamber	2–3
Pre-treatment vessel (acid wash)	2,000-litre HDPE tank with heating coil	1–1.5

Drying oven	200 kg capacity forced-air	0.8–1.2
Ball mill	50 kg/hr capacity, stainless liners	1.5–2.5
Total capital (excluding civil)		15–23 lakh
Civil works and commissioning		+2–4 lakh
Total installed		17–27 lakh

This capital requirement is within the range of NABARD-backed farmer cooperative lending schemes (KCC credit limits, FPO equity instruments, and SFAC grant support). A cooperative of 200 farmers contributing ₹10,000 each provides ₹20 lakh — sufficient to own the unit without external equity.

4.2 Feedstock Logistics

The paddy straw logistics model follows the existing paddy procurement infrastructure of Punjab. Rice is harvested in October–November. Paddy straw baling with tractor-mounted balers produces 15–20 kg cylindrical bales at a cost of approximately ₹150–200 per quintal (100 kg) including baling labour, fuel, and transport to the cooperative’s covered storage.

Per district unit processing 600 tonnes per year, feedstock requirement is approximately 800–900 tonnes of dry straw (accounting for 12–15% moisture in fresh bales). At ₹180/quintal, feedstock cost is ₹14.4–16.2 lakh per year — covered entirely by the hard carbon and carbon credit revenues with comfortable margin.

Storage: paddy straw bales must be stored under covered shelter to prevent rewetting (moisture above 20% promotes fungal growth and reduces pyrolysis carbon yield). A 1,000-tonne covered storage structure for one district unit requires approximately ₹3–5 lakh in semi-permanent shed construction.

4.3 Product Quality Control Pipeline

Quality control at district scale operates on a three-tier model:

Tier 1 — On-site gate (every batch): Raman spectroscopy D/G ratio measurement. A bench Raman spectrometer costs ₹8–15 lakh and is a Phase 1 cooperative investment. During Phase 0 at IIT Ropar, this measurement is performed externally. Pass threshold: $D/G > 1.0$. Fail trigger: repeat batch at adjusted temperature or extended hold time.

Tier 2 — Accredited lab monthly: XRD d_{002} (CECRI Karaikudi or IIT Ropar), BET surface area (ASTM D3663), and TGA ash content (ASTM E1131) on one representative sample per 10-batch tranche. Pass thresholds: $d_{002} = 0.37\text{--}0.40$ nm, BET < 50 m²/g, ash < 3%.

Tier 3 — Electrochemical certification per lot: Half-cell coin cell testing at CECRI or a certified battery testing facility for each 10-tonne production lot. Capacity certification issued at >300 mAh/g qualifies for Grade A pricing. Material in the 200–300 mAh/g range is sold as Grade B at ₹500–700/kg.

5. The Dual Revenue Model

5.1 Hard Carbon Anode Revenue

India's current hard carbon supply is almost entirely imported — from Japan (Kureha Corporation), China (domestic producers serving Chinese Na-ion manufacturers), and Europe. Import prices range from ₹800–1,500/kg depending on grade and specification. CATL's commercial expansion of Na-ion batteries to light commercial vehicles in 2026 signals the beginning of meaningful anode material demand at scale.

Domestic production at ₹800/kg for Grade A material (>300 mAh/g, d_{002} 0.37–0.40 nm, ash <3%) is competitive with imported material on price while offering supply chain security advantages for Indian cell manufacturers. Addressable market: if India deploys 1 GWh of Na-ion stationary storage by 2028 (a conservative estimate given central and state storage procurement mandates), the required anode mass is approximately 5,000–7,000 tonnes at 5–7 kg anode material per kWh. A single district cooperative producing 120 tonnes per year captures 1.7–2.4% of that demand.

5.2 Carbon Credit Revenue

Avoided paddy straw burning generates carbon credits certifiable under Verra VM0042 (Improved Agricultural Land Management v2.2), which covers avoided crop residue burning. Additionality — the requirement that credits represent emissions reductions that would not occur without the project — is established by the enforcement gap: Punjab's state-level paddy straw burning ban has been in place since 2018 but actual enforcement and alternative-use penetration remains below 10% of total straw volume. The gap between ban and compliance constitutes genuine additionality under VM0042 methodology.

Net CO₂-equivalent reduction per tonne of paddy straw diverted from burning:

- CO₂ avoided from combustion: approximately 1,460 kg CO₂/tonne (Jain et al., 2014)
- Minus CO₂ released during pyrolysis: approximately 180–220 kg CO₂/tonne
- Carbon locked in hard carbon anode (10+ year battery life): 180 kg C = 660 kg CO₂-equivalent
- Carbon locked in biochar returned to soil (100+ year stability): 90 kg C
- Black carbon (PM soot) avoidance: approximately 3 kg per tonne, with GWP of 900 (20-year horizon) = approximately 2,700 kg CO₂-eq for the

black carbon fraction alone, though conservative credit methodologies typically exclude this

Conservative net credit: 680–990 kg CO₂-eq per tonne of paddy straw (using the lower bound that excludes black carbon credits pending methodology confirmation with a Verra-certified consultant).

At a voluntary carbon market price of ₹500–1,500 per tonne CO₂-eq (2024 VCM range for high-quality agricultural credits with strong co-benefits documentation), a district unit processing 800 tonnes of straw per year generates 544–792 tonnes CO₂-eq in credits annually, worth ₹2.7–11.9 lakh per year. This is a secondary revenue stream that materially improves the cooperative's financial resilience but is not the primary commercial driver.

5.3 Cooperative Ownership Structure

The legal structure is a Multi-State Cooperative Society or State-level cooperative registered under the relevant Cooperative Societies Act, with the following distribution of net revenues:

1. Feedstock payment to farmer-members: ₹180–200 per quintal for straw delivered to cooperative storage (above the alternative of burning for zero return)
2. Operating costs: labour, reagents (HCl or NaOH), nitrogen gas, electricity
3. Loan repayment: if initial capital was borrowed
4. Member dividend: proportional to straw delivered

The ownership model ensures that value from the paddy straw — currently extracted as externality (health damage, crop field clearance) — accrues to the farming community rather than to external investors. The cooperative structure also aligns with government procurement preferences (DPIIT cooperative-sector priority in public tenders) and with Verra's community project requirements for VM0042 certification.

6. Environmental and Social Impact

6.1 Elimination of Straw Burning

The primary environmental benefit is the elimination of paddy straw burning in the cooperative's catchment area. Each tonne of straw diverted from burning avoids emission of 3 kg PM_{2.5} (fine particulate), 60 kg CO (carbon monoxide), and 1,460 kg CO₂. At 800 tonnes per district unit, annual emission reductions are: 2.4 tonnes PM_{2.5}, 48 tonnes CO, and approximately 990 tonnes net CO₂-equivalent.

PM_{2.5} emission reduction is the highest-value co-benefit. The social cost of PM_{2.5} from paddy straw burning in northern India is estimated at USD 3.2 billion per year across the region (Lan et al., 2022). A district-scale unit eliminating 800 tonnes of burning represents meaningful local air quality improvement, particularly given that burning is spatially concentrated in October–November when atmospheric inversion traps smoke over the Indo-Gangetic Plain.

6.2 Farmer Income Supplementation

The current economic situation for a paddy farmer in Punjab: - Paddy straw is a cost liability: burning it is free, but mechanical management costs ₹2,000–3,500/acre - This cost is borne by the state through Happy Seeder subsidies or absorbed as stubble-burning fines

Under the cooperative model: - Farmer earns ₹180–200/quintal for straw delivered to the cooperative - Average paddy straw yield per acre in Punjab: 25–30 quintals - Income per acre from straw: ₹4,500–6,000 - This income is currently zero — the conversion from liability to income is the behavioural incentive

6.3 Circular Economy Alignment

The process exhibits multiple material circularity features:

- Syngas self-heating: pyrolysis-generated syngas (CO , H_2 , CH_4) is recirculated as kiln fuel, covering 60–90% of the thermal energy input and approaching energy autonomy
 - Sodium silicate by-product: NaOH pre-treatment produces water glass for sale to cement or paper industries
 - Biochar soil amendment: biochar returned to agricultural soil in the cooperative's catchment closes the carbon cycle, improves soil water retention, and qualifies for VM0044 carbon credits
 - Process water: effluent from acid wash neutralised and used for field irrigation (pH-adjusted to 6.5–7.5 before release)
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7. Novel Contributions

This paper makes the following novel contributions to the intersection of electrochemical materials science, frugal manufacturing, and agricultural cooperative economics:

1. **Process characterisation of Punjab paddy straw as Na-ion hard carbon precursor.** While rice husk (same genus, different plant part) has been extensively characterised, paddy straw (the stem and leaf residue) has distinct silica distribution, cellulose content (38–47%), and lignin content (5.6–11.6%) profiles that affect hard carbon yield and structure. This paper provides the first integrated process specification — from HCl silica removal through pyrolysis parameter optimisation to quality control protocol — for paddy straw specifically, rather than rice husk analogues.
2. **District-cooperative capital architecture at ₹15–25 lakh for Na-ion grade production.** Existing literature on hard carbon manufacturing addresses laboratory-scale or gigafactory-scale routes. This paper designs the intermediate case: a cooperative-scale retort kiln producing 120–140 tonnes per year, with complete capital bill-of-materials, at a cost level that enables farmer-cooperative ownership. This architecture has not been previously documented in the materials science literature.

3. **Dual-revenue model combining battery anode sales with carbon credit certification.** The economic viability of paddy straw valorisation has been studied in the biogas, composting, and mushroom cultivation literature. The combination of a premium industrial product (Na-ion anode material) with carbon credits under VM0042 (avoided burning) and VM0044 (biochar) generates a revenue profile that no single application achieves alone. The dual-revenue structure is the enabling mechanism for cooperative-scale economics.
 4. **Syngas self-heating loop for near-energy-autonomous pyrolysis.** The thermodynamic analysis of paddy straw pyrolysis at 1,100°C identifies syngas energy content (1,200–1,800 MJ/tonne) as sufficient to cover 60–90% of the endothermic pyrolysis heat demand (1,500–2,000 MJ/tonne), with bio-oil recirculation closing the balance. An appropriately designed retort kiln with syngas recirculation combustion chamber achieves near-energy-autonomy at this scale — a significant operational cost reduction not achievable at laboratory scale (where small reactor surface area-to-volume ratio creates proportionally large heat losses).
 5. **Additionality framework for carbon credits under Punjab burning ban.** The Verra VM0042 methodology requires demonstration that emission reductions would not occur without the carbon project (additionality). Punjab's state burning ban creates apparent complexity — if burning is already banned, how can avoiding it generate credits? This paper articulates the enforcement gap argument: the ban exists but actual collection and alternative use of paddy straw remains below 10% of total volume, and the economic barrier (cost of straw management) is the operative constraint. Providing paid collection eliminates the economic barrier, enabling genuine additionality even in the presence of the ban. This framework is novel in the carbon credit design literature for Indian agricultural contexts.
 6. **Three-tier quality control protocol for cooperative-scale battery materials production.** Existing battery materials quality control literature addresses either laboratory characterisation or industrial inline inspection — both out of reach for a district cooperative. This paper designs a three-tier protocol: (Tier 1) on-site Raman D/G ratio as a 5-minute batch gate; (Tier 2) monthly accredited XRD/BET panel at IIT Ropar or CECRI; (Tier 3) electrochemical half-cell certification per production lot. This protocol maintains international grade certification standards within a rural cooperative's operational and financial constraints.
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8. Conclusion

The convergence of three trends — the global expansion of sodium-ion batteries to commercial vehicle and stationary storage applications, India's annual 20+ million tonne paddy straw burning crisis, and the growing body of literature establishing agricultural biomass as a viable hard carbon precursor — creates a tractable engineering and economic problem. Hard carbon from paddy straw at 1,100°C pyrolysis produces material with $d_{002} = 0.37\text{--}0.40$ nm, BET surface area of 10–50 m²/g, and reversible Na-ion

capacity of 300–350 mAh/g based on analogous rice-family biomass data. The chemistry is established. The capital cost for a district-scale retort kiln (₹15–25 lakh) is within cooperative ownership range. The dual-revenue model (hard carbon + carbon credits) makes the economics work without institutional capital.

The outstanding experimental gap is Phase 0 validation of Punjab paddy straw specifically: coin cell capacity measurement at C/10 in sodium half-cells, using material pyrolysed from HCl-washed PR 126 and PR 122 cultivar straw at 1,100°C. This is a 60–90 day laboratory programme at IIT Ropar, CECRI, or any institution with a battery cyclers and a tube furnace. The pass threshold is 150 mAh/g at C/10 — well below the 300+ mAh/g demonstrated for rice husk at comparable pyrolysis conditions. The precaution of a lower threshold acknowledges cultivar and straw-versus-husk morphology differences.

If Phase 0 validation confirms the capacity threshold, the path from paddy field to sodium-ion battery anode — via district cooperative ownership, farmer income, air quality improvement, and carbon credit generation — is fully specified. This paper places that specification in the public domain.

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This document is a defensive publication filed to place the described process architecture, manufacturing model, and economic design in the public domain. PowerPbox IT Solutions Pvt. Ltd. does not claim patent rights over material disclosed herein. The purpose of this publication is to ensure that the district-cooperative hard carbon manufacturing model and dual-revenue structure are freely available to any agricultural cooperative, development organisation, or battery materials company that wishes to implement them, particularly in India and other rice-producing developing economies.

Technical validation of Phase 0 capacity data is in progress at IIT Ropar, Punjab, India.

Contact: PowerPbox IT Solutions Pvt. Ltd. · ANKR Platform **Submission**
date: 2026-03-25 **Document type:** Defensive Publication / Preprint **Zenodo-**
ready: Yes