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Cow dung valorization via dual-stream separation: An integrated LCA and techno-economic framework for agricultural and algal use

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ABSTRACT

Cow dung, often left unmanaged, represents both a nutrient source and an emissions burden. Here we report a decentralized hydraulic process that separates fresh, wet cow dung into two usable streams: a fibrous solid and a nutrient-rich liquid. Pressing removed ~ 80 % of moisture with fibre recovery of 87 %, yielding materials that supported both plant and algal growth. Fibre application increased the germination energy of Vigna radiata by 47.6 %, while the nutrient powder, obtained through freeze-drying, sustained algal cultures more effectively than synthetic f/2 medium. Life cycle analysis identified freeze-drying as the main environmental hotspot, contributing over half of the system's climate footprint (~0.84 kg CO_2-eq per 0.5 kg processed). Scenario modelling showed that solar or hybrid drying could reduce this impact by more than 90 %. A multitask neural network (R2 = 0.79) predicted product yields from raw input, supporting process optimization. Techno-economic evaluation indicated a net loss at bench scale, but break-even and positive returns when deployed in *gauśāla* settings, where local use and market-linked fibre and nutrient streams offset costs. This dual-stream approach demonstrates that cow dung can be reorganized into structured outputs without secondary effluents. By combining experimental validation, life cycle metrics, and economic modelling, the study provides a realistic pathway for circular bio-resource management under decentralized rural conditions.

Introduction

Livestock-related greenhouse gas emissions remain a subject of sustained global attention (Ivanovich et al., 2023; "Modern food emissions," 2023). In India, the discussion becomes more layered: cattle are part of both farming infrastructure and cultural heritage. As a result, the way cow dung is perceived and managed shifts across contexts, what qualifies as discardable in one setting may be preserved or valued in another. India accounts for over 12 % of the global cattle population (Patra, 2014), but most livestock are reared in small, decentralized units. As a result, dung disposal is inconsistent and often unmanaged, contributing to methane and nitrous oxide emissions (https://www.ghgplatform-india.org). The fragmented nature of the collection adds logistical barriers to standardized treatment.

Enteric fermentation, which occurs during digestion, is the primary source of livestock-related methane emissions. It contributes nearly 90 % of the total. However, dung stored under wet, oxygen-poor conditions also produces CH_4 and N_2O, especially in hot climates (Van Der Weerden et al., 2021). Efforts to manage enteric methane have examined feed-based modifications; among them, seaweed additives have received particular attention. Dung-handling measures, by contrast, tend to favour small-scale biogas conversion. India's *Gobardhan* programme (2021) promotes this method, though outcomes remain uneven, shaped by local resource flows, upkeep constraints, and operational stability.

Biogas systems beyond India have seen uneven outcomes. In areas like Ethiopia and Zambia, water shortages and infrastructure limitations have posed obstacles (Nevzorova and Kutcherov, 2019; Arango et al., 2020). Although purification levels of greater than 90 % methane are

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technically achievable (Mao et al., 2015), their practical adoption remains slow, partly due to policy and logistical concerns (Abatzoglou and Boivin, 2009). Sun-drying remains a fallback method in many rural settings, despite its dependence on favourable weather and limited processing efficiency. The chemical makeup of fresh cow dung includes structural carbohydrates such as cellulose and lignin, along with micronutrients and microbial compounds (Cao and Harris, 2010; Gupta et al., 2016; Mohan et al., 2021). However, the material is also high in moisture, often exceeding 80 %, which accelerates microbial activity and shortens its usable duration. This compositional richness also invites selective recovery pathways if moisture can be reliably controlled. Any effort to convert cow dung into value-added outputs depends first on stable pre-treatment. Drying is not a peripheral step; it is foundational. Rotary drying processes are known to emit high volatile organic compounds at higher temperatures and expensive compared to other systems (Pang and Mujumdar, 2010). In comparison, microwave-based methods have shown better energy profiles when applied after partial moisture removal (Guo et al., 2023). A variety of mechanical approaches have been tested to divide cow dung into solid and liquid parts. These include screen-based systems, screw-driven presses, and centrifugal separators (Aguirre-Villegas et al., 2019; Møller, 2000). These methods are often adapted for dairy slurry or biogas residue and can generate secondary effluents, complicating decentralized use.

In this work, we introduce a TRL 2–3 hydraulic system designed to process fresh cow dung into two output streams: a fibrous solid and a nutrient-rich liquid. The solid may be dried or carbonized; the liquid is stabilized through drying for reuse. Both are retained. The process avoids secondary effluent and supports on-site use in *gauśālas* or similar rural facilities. In this paper, we have hypothesized that cow dung, in its native form, possesses both micro- and macro-nutrients, along with fibrous materials, which contribute to the concept of resource recovery, ultimately leading to a bio-circular economy. Literature also suggests that the hydraulic press is one of the cheapest alternatives. The non-Newtonian behaviour of cow dung leads to the hydraulic pressing, and we conducted a LCA to monitor the overall process.

Materials and methods

Instruments

The surface morphology was analyzed using a Field Emission Scanning Electron Microscope (Carl Zeiss Gemini SEM 300 Germany). Supercritical fluid carbon dioxide at 40 °C and 350 bar in a pilot plant supplied by Deven Supercritical Private Limited, Daman, India used for Super Critical Fluid (SCF) extraction. 5975C Inert Mass Selective Detector (MSD) with Triple Axis Detector and Column DB-5MS UI, Length – 30 m, Diametor-0.250 mm, Film thickness-0.25(um) was used for Gas chromatography- Mass Spectrometry (GC–MS) analysis.

Materials

The raw cow dung of Kangayam- Bos indicus breed was collected from Mr. Natarajan, Sukkaliyur town, Karur, Tamilnadu, India (10.9606360°N, 78.076520°E). Sodium Chloride (NaCl), Potassium Chloride (KCl), and Calcium Chloride ($CaCl_2$) were purchased from Sigma Aldrich. All chemicals were of Emplura grade from Merck Life Sciences, India. ASTM Type I water obtained using the PURELAB Quest UV Elga water purification system was used for all process and washing purposes. All glassware used throughout the experimentation was of ASTM specifications obtained from Borosil Limited, Mumbai.

Methods

Fresh raw, wet cow dung was collected and sealed in polypropylene bags from the farm. The collected samples were mixed thoroughly by hand and shaped into one large ball. 300 g of this cow dung was placed in a polymeric filter fabric. A pressure of 10 to 12 bar was applied using the hydraulic piston, and the pressure was then released. The obtained squeeze (liquid) is dried using a lyophilizer, and the lyophilized powder and the dried Fibre were digested using a microwave digester. Digested solutions were checked for nutrient amount with the 884 computrace trace metal analyzer as well as ION selective electrodes. The digested solutions of these were used for algal culture, and the dried Fibre was used for studying the growth of *Vigna radita L.* A cradle-to-grave LCA analysis and a techno-economic analysis of the process were also conducted. (Detailed procedure for each is given in the Supplementary section).

Results and discussion

The developed physical separation process

The hydraulic pressing of raw wet cow dung enables separation into liquid and fibrous components, targeting its inherent moisture-structural complexity. This separation allows for high-yield valorization with minimal waste. The liquid ("squeeze") and the fibrous residue ("cake") were separated under 10–12 bar pressure. The cake peeled easily from the filter cloth, indicating effective dewatering. The process yielded an average of 145 ± 5 g of liquid and 140 ± 5 g of moist fibre from 300 g of fresh cow dung (75 % moisture). The fibre mass includes residual moisture (~45–55 %), with actual dry mass recovery approximating 87 ± 3 g. The overall Process Recovery Efficiency (PRE), defined as the mass of usable output (liquid + fibre) over input, was 81.6 %. A minor fraction (~10–12 %) of mass was unaccounted for due to sludge adhesion, capillary loss, and filter retention. Full mass balance is provided in Supplementary Table S3a. The fibrous cake was dried in a hot air oven to constant weight. FESEM images of the filter cloth pre- and post-pressing are shown in Fig. 1a–d. Supplementary Tables 1 and 2 describe the process parameters and fabric characteristics.

A brief description of the process is presented to expound on its efficiency. The raw wet cow dung contains 830 kg of water per 1 ton of the dung (Xin et al., 2018), (https://tinyurl.com/2kfjr3w7). According to the numeric indicated in the mass balance, 665 kg of water is eliminated during the process, which gives an overall water removal efficiency of ~ 80 %; the remaining 20 % is lost in the filter cloth, and this loss is unavoidable. The total energy consumption for the sequential process (our developed technology) is 630 kWh/ton. This value is comparable to the 552 kWh/ton predicted for the cow dung drying process in a rotary dryer (De Azevedo et al., 2017). The use of the excess 78 kWh/ton by our process results in two high-quality end products rather than merely separating the water from the raw wet cow dung. Hence, the developed process is superior in terms of end-product quality, environmental safety, and energy efficiency. Disposing of the liquid part is environmentally a burden, and a processing technique with zero per cent effluent is essential under the climate change regime. The processing of the separated liquid part for nutrient recovery has an energy burden of 500 kWh/ton, which is inclusive of the overall energy demand of 630 kWh/ton.

In contrast to conventional manure separation systems such as screw presses, belt presses, or centrifuges, which are widely used in industrial dairy and anaerobic digestion plants, the system proposed in this study is intentionally designed for low-cost, decentralized rural contexts. The hydraulic pressing mechanism described here is not intended as a technical competitor to commercial rotary or continuous-flow separators. Rather, it is framed as a contextual, frugally engineered alternative that can be deployed in environments where: Capital investment exceeding ₹1 lakh is not viable and Electrical power is intermittent or unavailable. Maintenance must be carried out by local operators without advanced tools. Batch-mode operation is preferred due to decentralized input supply (e.g., *gauśāla*, farm clusters, or village-level composting units).

The engineering design is grounded in principles of non-rotary,

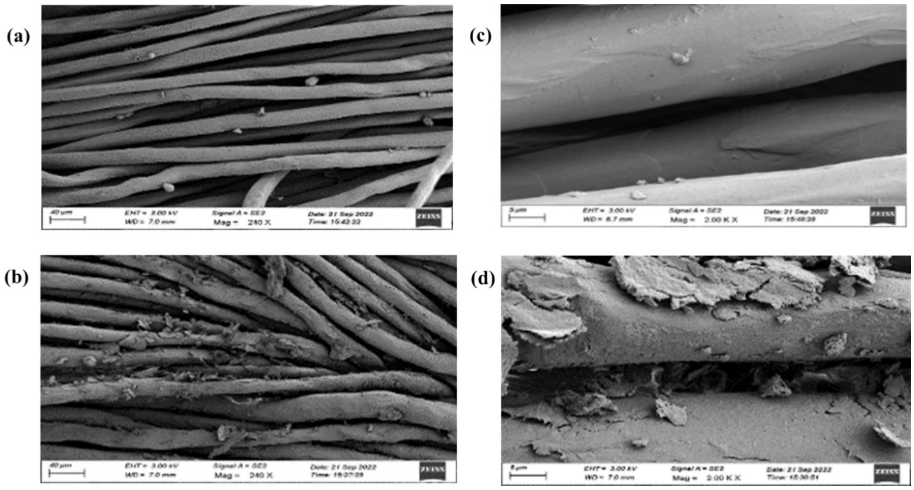

Fig. 1. a) and b) FESEM images of filter cloth before pressing, c) and d) FESEM images of filter cloth after 30 presses.

manually operable, and failure-tolerant systems, with the goal of enabling micro-scale waste valorization without dependence on centralized infrastructure. This distinction is crucial to interpreting the feasibility and economic assumptions presented in later sections of the study. While the initial prototype utilized a polyester-based filter cloth to achieve solid–liquid separation under low-pressure hydraulic pressing, the embedded energy and material footprint of this component present a clear limitation for scalability. As quantified in Section 3.6.3, scaling the cloth-based design to industrial levels would require ~ 100 m^2 of fabric, translating to 0.885 kWh of embedded energy and approximately 0.7257 kg CO_2 equivalent emissions, rendering it unsuitable for sustainable deployment at large volumes.

In recognition of this limitation, the present study proposes a conceptual transition toward a cloth-free filtration system based on perforated stainless-steel mesh or plate elements. The objective is to reduce material replacement frequency, enhance pressure durability, and improve long-term operability in decentralized environments. A preliminary gravity-based test using a 300-μm perforated steel mesh demonstrated visual separation of liquid and fibre fractions (see Supplementary Fig. S1). However, full mechanical pressing trials with mesh media have not yet been completed. As such, the mesh pathway is introduced as a forward-looking engineering direction, not as a validated replacement at this stage. Future work will involve optimization of pore geometry, pressure-drop characteristics, clogging resistance, and long-term performance evaluation under field conditions. In order to locate the present study within the broader technological landscape of manure separation, Supplementary Table S3 presents a comparative overview of commonly used separation systems, including screw presses, belt presses, and centrifuges, alongside the proposed low-pressure hydraulic pressing unit. Rather than positioning itself within the conventional axis of throughput or automation, the proposed design follows a different principle of sufficiency: it aims to be locally fabricable, energy-frugal, and functionally adequate for decentralized rural contexts where the burden of manure accumulation is real but industrial systems are often economically or operationally out of reach.

The comparative framework is not intended as a performance contest, but as a boundary map of contextual viability, where energy, capital, and maintenance form a triad that governs whether a technology can truly be sustained at source. The hydraulic press, in this light, offers a recursive value: not to outcompete, but to enable separation where nothing else may arrive.

The nutrient recovery is done by freeze-drying the separated liquid from raw wet cow dung. Freeze-drying is an energy-intensive process, and this technological aspect is widely accepted and acknowledged, but recent innovations have revolutionized the freeze-drying industry. The disposal or reuse of the accumulated ice from the freeze-drying process has less environmental burden. Thus, the current freeze-drying process is advocated for nutrient recovery, which is admissible in the present scenario. A nutrient-concentrated powder having multifaceted applications is recovered ~ 19 kg per ton of raw wet cow dung. Its usage in algal cultivation is mentioned under section 3.6 in the current manuscript.

While lyophilization was employed in this study to preserve the micronutrient-rich liquid extract and facilitate controlled nutrient experiments with *Chlorella vulgaris,* we acknowledge that it represents a high-energy operation unsuitable for rural deployment. Its inclusion here is solely for scientific validation, and not as a prescriptive process step. In practical scenarios, low-energy alternatives such as solar-assisted tray drying, membrane evaporation, or biodrying are recommended. A 4E (energy–exergy–environment–economic) comparison places low-temperature convective hot-air and hybrid routes as context-appropriate substitutes to freeze-drying when products are not heat-labile (Martynenko and Alves Vieira, 2023). Membrane concentration of the liquid fraction is a viable preservation alternative that couples nutrient removal with recovery for reuse (Zielińska and Bułkowska, 2025). Hence, lyophilization in this work is an intermediate stabilization step, not a necessary technology component for scalable field application

The processed cow dung Fibre is a good fertilizer for agriculture and house gardens. A preliminary 18-day study (described in section 3.4) on the sprouting and growth of *Vigna radita L.* (Green gram) suggests that processed cow dung Fibre aids in improving the germination capacity and germination energy of the seeds. The developed process preserves the bioactive molecules inherently present in the cow dung. In this manuscript, we report the extraction of bioactive molecules using supercritical fluid CO_2 with ethanol as the co-solvent in Section 3.3. Further, processed cow dung Fibre is an apt raw material for depolymerizing inherent macromolecules like lignin, cellulose, and hemicellulose (Fasake et al., 2021). The breaking down of cellulose and hemicellulose to hexa/penta-sugar gives accessibility to bioethanol, fuels and platform chemicals (Jang et al., 2012) (Chaabouni et al., 2014), (Pulicharla et al., 2016), (Li et al., 2024), (Wang and Rijal, 2024).

A multitask learning model using neural network

This comprehensive analysis evaluates a multitask learning (MTL) method for predicting three output features, liquid after squeeze (O1), weight after squeeze (O2), and weight after drying (O3), from one input variable: weight of raw cow dung. The MTL model has a shared foundation layer for processing the input variable and a task-specific branch, where the output layer has individual linear layers for each target variable. The MTL loss is computed as a sum of the losses computed for each of the output variables. We implemented a five-fold stratified five-fold cross-validation to ensure reproducible results. We used the R2-score and RMSE (root mean squared error) to evaluate the model's performance.

From Table 1, it is evident that the model performs poorly for O1 with a high variability across 5 folds. This low score indicates that the features have limited predictive value for O1, or the underlying relationship is weak. RMSE value supports this observation. The model exhibited strong R2-score values for O2 and O3 with low variability. However, the high RMSE obtained for O2 indicates the high variability iβn the data, whereas the low RMSE obtained for O3 confirms the accurate and consistent prediction.

In Table 2 the higher correlations between predicted values compared to true values, particularly for O1 relationships, indicate that the network learns to predict O1 based on patterns from O2 and O3 rather than discovering direct input-feature relationships. The high cross-output correlations in predictions (0.77–0.98) compared to true correlations (0.07–0.80) demonstrate that the proposed model successfully transfers learned representations between tasks. However, the higher difference between the predicted and true correlation values suggests that the MTL network is learning artificial dependencies between the output variables that do not exist in the data.

In summary, the MTL model demonstrates high accuracy for O2 and O3. However, its performance for O1 is limited, and the model tends to overestimate the input–output correlations. Key relationships and validation plots are represented in Fig. 2a-c.

Correlation between GC–MS analysis and antimicrobial activity of fibre extracts

The scf/CO_2 + ethanol extract exhibited the most prominent zone of inhibition among all samples. GC–MS analysis revealed a high abundance of benzyl isothiocyanate and hexanoic acid—compounds previously associated with antimicrobial action. The Soxhlet ethanol extract, while active, showed a dose-dependent response with narrower inhibition zones. This activity is attributed to moderate levels of pyrimidinone derivatives and long-chain fatty acids. Comparative visual assays and GC–MS data suggest that the SCF extract possesses higher inhibitory potential, likely due to its enriched volatile profile. While preliminary, these results indicate that fibre-derived extracts may support the development of natural, bio-based antimicrobial formulations for sustainable hygiene applications. Minimum inhibitory concentration (MIC) values and standard antibiotic comparisons will be included in future trials to further benchmark efficacy. Fig. 3a and b represent the antimicrobial activity of the scf/CO_2 extract and ethanol extract. Fig. 3a S1, which represents the scf/CO_2 extract, shows an inhibition zone of 8.265 mm against *S. aureus,* and Fig. 3b, which represents the ethanol extract, shows an inhibition zone of 3.923 mm, which is comparable with the std, having an inhibition zone of 4.8 mm.

The extracted compounds, while preliminary in identification, may serve as bioactive agents either independently or as enhancers in combination with conventional antimicrobials, potentially lowering the dosage of synthetic additives. This is particularly relevant in the context of post-COVID hygiene trends, where disinfectants, floor cleaners, and hand sanitizers have gained significant market share. Many of these formulations are alcohol-based and carry associated environmental risks. In this regard, water-based systems containing naturally derived antimicrobials from non-food biowastes offer a desirable, low-impact alternative (Chen et al., 2022), (McClements et al., 2021), (Maia and Moore, 2011). Fig. 3c-f represent the most abundant components present in each extract of fibre, which is then used for antimicrobial analysis.

Table 1
5-fold cross-validation performance analysis of the proposed MTL model for predicting the three output variables from one input variable.

Feature	R^2-score	RMSE
O1	0.2036 ± 0.1803	61.0000 ± 6.8501
O2	0.7274 ± 0.0661	75.0454 ± 6.8167
O3	0.7833 ± 0.0540	13.6186 ± 1.4144

Table 2
Cross-output correlation analysis for predicted and true values.

Correlation Type	Predicted values	True values	Difference
O1-O2	0.7744	0.0717	0.7027
O1-O3	0.8246	0.3849	0.4397
O2-O3	0.9797	0.8038	0.1759

Agricultural evaluation of processed fibre on Vigna radiata L

A preliminary growth study was conducted using green gram (*Vigna radiata L.*) seeds under three fertilization treatments: (1) red soil only, (2) red soil + commercial cow manure, and (3) red soil + processed cow dung fibre developed in our lab which is having higher presence of Hemicellulose followed by Lignin and Cellulose respectively which was calculated using NREL method. The evaluation considered early germination, plant morphology, and leaf development.

In all three cases, the first germination occurred on the 6th day and the first leaf on the 7th day. The germination energy increased exponentially from the soil group to the processed fibre group. Further, theTable 3 indicates that the processed fibre group has a potential germination energy of 5 times higher than the soil. Interestingly, the processed cow dung fibre performs exceedingly well compared to commercial cow dung powder. The germination capacity was equal for the commercial cow dung powder and processed cow dung fibre groups. Both these groups performed better than the soil group. Based on the difference in germination energy and germination capacity, the group performance can be attributed to seed dormancy (Finch-Savage and Leubner-Metzger, 2006), (Penfield, 2017). In all the other investigated physical parameters like stem height, leaf length and breadth, the processed cow dung fibre exceeds both the groups. These findings suggest that processed cow dung fibre may serve as a high-performance, bio-derived soil enhancer, with benefits extending beyond traditional manure.

Algal growth response to nutrient media

The optical growth study of *Chlorella vulgaris* over 14 days under six nutrient treatments was used to determine the most efficient cow dung-derived formulation for algal biomass enhancement. No sterilization and chemical treatment were applied to the digests prior to the algal population, in order to reflect natural compatibility and realistic use-case potential. The nutrient media included: (1) standard f/2 medium, (2) fibre digest, (3) lyophilized powder digest, and three binary mixtures (i) f/2 + fibre digest (ii) f/2 + lyophilized powder digest and (iii) fibre digest + lyophilized powder digest. Complementary studies show that microalgae can be grown directly on liquid digestate under sunlight in non-sterile conditions with concurrent nutrient removal (Sobolewska et al., 2024).

The lyophilized powder digest, which contained elevated levels of Ca (23.72 ppm), K (11.59 ppm), Na (7.91 ppm), Zn (1.74 ppm), and Cu (0.21 ppm), showed the most vigorous algal growth (Suthar and Verma, 2018), (Chakraborty et al., 2023). These observations align with the broader role of cyanobacteria and microalgae as agricultural bio-inputs that support nutrient cycling and plant performance (Nawaz et al., 2024). It supported fast biomass accumulation up to Day 10, after which it plateaued. The processed fibre digest, with significantly lower total metal concentration (0.63 ppm), supported slower and plateaued growth. The binary combination of lyophilized powder and fibre digest

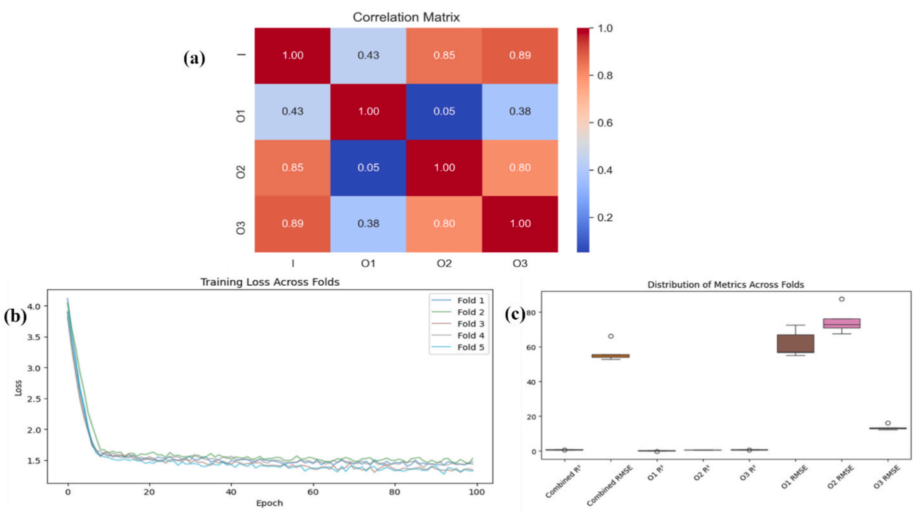

Fig. 2. a) correlation matrix heatmap used to explore relationships among input (raw cow dung weight) and predicted outputs (o1–o3) prior to model training. b) five-fold cross-validation loss plot showing model convergence and internal consistency across training cycles. c) box plot of r^2 and RMSE values across all folds, used as a diagnostic tool to evaluate model variance and predictive stability.

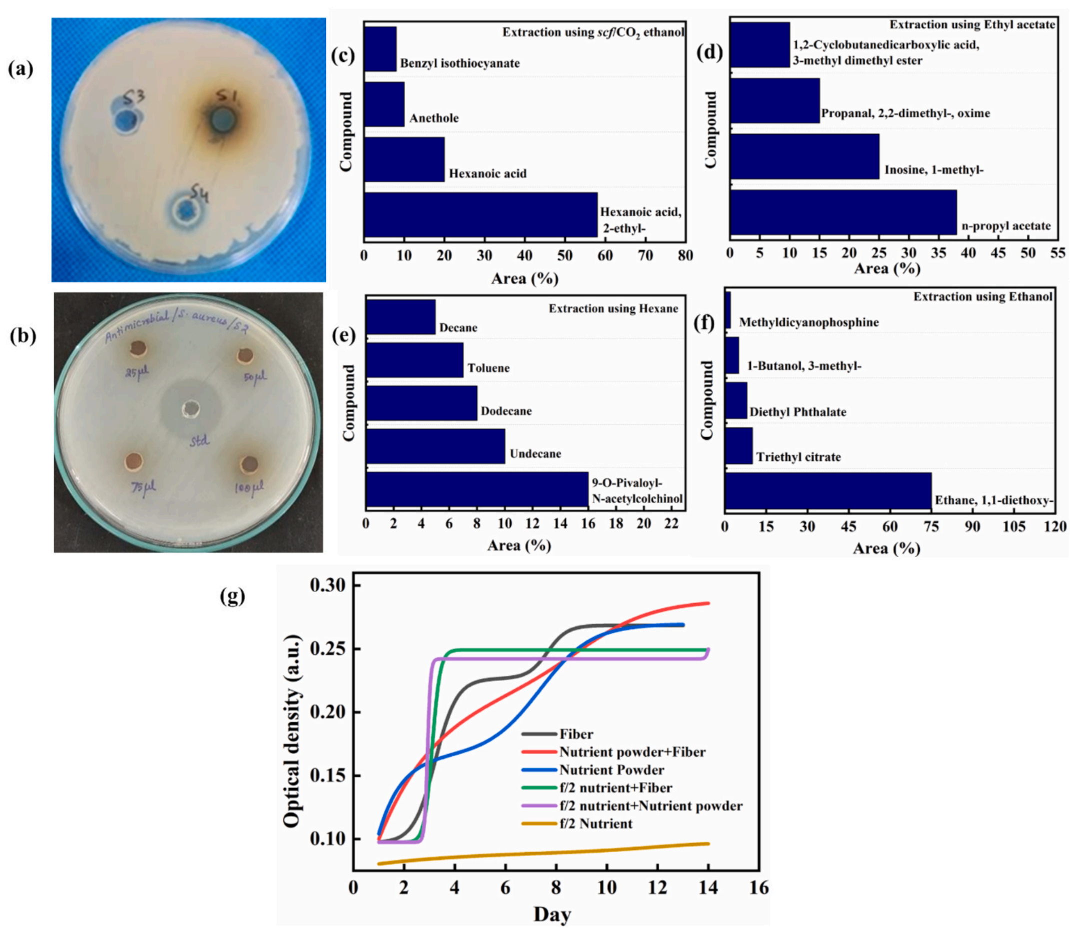

Fig. 3. a) antimicrobial activity of *scf/CO₂* ethanol extract, b) Antimicrobial activity of Soxhlet ethanol extract, c) Fibre *scf/CO₂* ethanol extract, d) Fibre ethanol extract, e) Fibre hexane extract, f) Fibre ethyl acetate extract, g) Algae growth evaluated using optical growth density.

(L + F) outperformed all other treatments, suggesting synergistic nutrient effects. In contrast, standard f/2 medium alone led to the lowest growth, reflecting its lack of supplementary micronutrients. Nutrient elements present in both lyophilized powder digest and fibre digest are given in the Table 4.

The superior performance of lyophilized digest, particularly in combination with fibre, is attributed to its balanced macro- and micro-nutrient profile, which aligns with the physiological needs of *Chlorella vulgaris*. The binary mix (L + F) offered both rapid and sustained nutrient availability, promoting exponential growth through Day 14. The results

Table 3
Preliminary data on agricultural studies.

Growth Parameter	Soil Only	Soil + Manure	Soil + Fibre
Germination Energy (%)	9.52	23.81	47.62
Germination Capacity (%)	76.19	85.71	85.71
Stem Height (cm)	5.0	5.0	5.5
Leaf Breadth (cm)	4.0	3.5	4.0

affirm that cow dung-derived digestates, especially when processed and combined, serve as effective nutrient sources for sustainable algal cultivation. Although the f/2 medium is a widely accepted standard for algal cultivation, the optical growth analysis revealed that it supported the lowest biomass yield among the six treatments. The f/2 medium provides nutrients in synthetic inorganic forms, which may not be as readily bioavailable to *Chlorella vulgaris* as the organically bound nutrients present in cow dung-derived digests. Even though the processed fibre has lower total nutrient content, the presence of naturally occurring micronutrients such as zinc and copper in chelated or organic-bound forms could enhance uptake efficiency. Cow dung fibre digest may contain humic substances, plant growth regulators, or amino acids that are absent in synthetic media. These compounds are known to stimulate algal metabolism, photosynthesis, and chlorophyll synthesis, thus compensating for lower metal concentrations. Cow dung digestates may also contribute organic or inorganic carbon sources (e.g., bicarbonates), which are not present in f/2. This could facilitate additional carbon fixation, leading to improved photosynthetic rates and cellular growth. The growth evaluated using optical density is represented in Fig. 3g. Such microscale digest valorization aligns with closed-loop principle in integrated waste processing systems. Quantitative dry weight and chlorophyll analyses are planned in the upcoming iterations to complement the current optical growth trends.

LCA analysis of developed process, cradle to gate

The present Life Cycle Assessment (LCA) investigates the environmental and economic performance of a laboratory-scale cow dung valorization system represented in Fig. 4. The study evaluates material flows, energy use, and impact outcomes across pressing, drying, lyophilization, and downstream applications. The study normalizes 0.5 kg of cow dung, which was used in laboratory conditions, to industrial systems. The functional unit used in this study is 0.5 kg of raw cow dung input. This value corresponds to the capacity of the experimental pressing cycle and was chosen to ensure traceable, lab-grounded material and energy flows without upscaling assumptions. While non-standard compared to LCA studies using per-ton units, this choice aligns with the batch-mode design logic of decentralized rural systems. This cradle-to-gate approach aligns with ISO 14040/44 standards and was informed by recent LCA studies on organic waste valorization (Tan et al., 2022), (Esteves et al., 2019).

Section 1: Goal and Scope Definition: Environmental impact per functional unit

The life cycle assessment of the cow dung valorization system, based on a functional unit of 0.5 kg fresh cow dung, revealed distinct environmental profiles for each unit operation. The total climate change impact amounted to 0.84 kg CO_2-eq**,** with lyophilization of the liquid fraction emerging as the dominant contributor (~51 %), primarily due to prolonged energy-intensive freeze-drying cycles (Ehlers et al., 2021). The microwave digestion contributed ~ 33 % of the CO_2-equivalent emissions, whereas the hydraulic pressing, oven drying of fibre, filter cloth usage for solid–liquid separation, filter cloth washing water usage, transport and equipment amortization collectively contribute the rest. Recent farm-scale LCAs report that deploying press-based solid–liquid separation upstream of storage can lower transport loads and downstream treatment burdens, improving net footprints (Zhang et al., 2023). In terms of cumulative energy demand, the system required 2.98 MJ, with lyophilization and microwave digestion jointly accounting for over 82.5 % of the total energy inputs. Water consumption, driven entirely by ASTM Type I water used in microwave digestion and algae culture media preparation, totalled 1.2 L per functional unit. While eutrophication potential and resource depletion were qualitatively tracked, preliminary estimates indicate that their contributions remain minimal due to the lab-scale nature of the operations and absence of chemical reagents. Notably, the mass allocation of co-products revealed that only 0.16 g of

Table 4
Nutrients present in the nutrient powder and processed fibre.

Sample name	Concentration(ppm)							Total metal present	Relative Concentration (%)
	Zn	Cd	Pb	Cu	Ca	K	Na		
Raw Cow dung	0.4287	0.1529	0.0378	BDL*	1.7168	3.2530	0.1509	2.4871	100 %
Processed fibre	0.4088	0.0335	0.0043	0.1838	BDL*	BDL*	BDL*	0.6304	25 %
Nutrients powder	1.7417	0.0081	0.0510	0.2087	23.7198	11.5924	7.9066	38.1123	1532 %

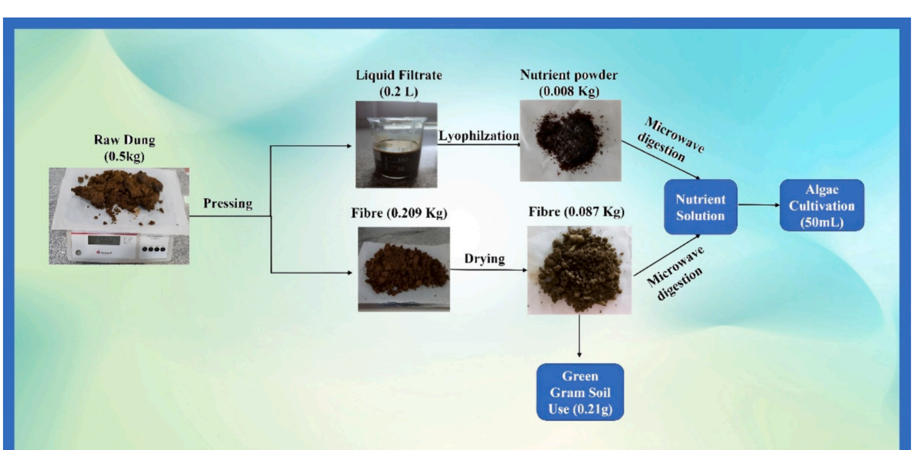

Fig. 4. LCA flow diagram.

lyophilized material was required for algal nutrient formulation, with the remainder classified as residual or inert storage. Similarly, the recovered fibre showed utility in green gram sprouting trials (0.21 g applied to soil), suggesting an efficient valorization pathway for solid fractions. The cradle-to-gate profile confirms the process viability and underscores the potential for optimization in energy recovery and thermal process integration in future scale-ups. Fig. 5a represents this in a graphical format.

Section 2: Life cycle inventory (LCI)

The life cycle inventory developed for the processing of 0.5 kg of raw cow dung delineates material and energy flows across six sequential stages: hydraulic pressing, drying, lyophilization, microwave digestion, nutrient blending, and biological application. The initial pressing operation yielded approximately 0.087 kg of solid fibre and 0.200 L of liquid filtrate, corresponding to a fibre yield of 17.4 % by mass. The hydraulic press consumes an energy of 0.0155 kWh, additionally with an embedded energy for filter cloth usage for 100 g of raw wet cow dung in 0.25 m^2 as 0.136 kWh. The solid fibre underwent oven drying at 60 °C for 3–4 h, consuming approximately 0.003 kWh per functional unit. Simultaneously, the liquid fraction was lyophilized to produce 8.0 g of powder, at an energy cost of 0.528 kWh per batch. Both the dried fibre and the lyophilized powder were independently subjected to microwave digestion (600 W, 30 min), each requiring ~ 0.3 kWh, followed by dilution with ASTM Type I water to obtain two 25 mL nutrient solutions. These were combined to form a 50 mL integrated growth medium, which supported a 14-day (later extended to 21-day) batch culture of microalgae (Collet et al., 2011). In parallel, 0.210 g of dried fibre was directly applied to soil for green gram sprouting trials, representing the agricultural end-use stream. Notably, only 0.160 g of each material (fibre and lyophilized powder) was consumed for nutrient preparation, while the remaining > 98 % of lyophilized powder and unused fibre residue were excluded from impact allocation, following a mass-based partitioning approach. In the algal growth studies, only 0.16 g of lyophilized nutrient powder (from a 4 g batch) was functionally deployed, leading to an inflated per-gram GWP when full lyophilization energy was attributed to this fraction. To correct for this, a dual-allocation scenario is now presented (Supplementary Table S9), showing that full powder-based allocation reduces the apparent GWP per gram by over 95 %. Future work will utilize the entire powder yield, thereby diluting this energy footprint across broader application pathways." The output quantification of algae biomass remains simulation-based due to ongoing experimental validation, whereas the green gram trial demonstrated viable soil integration. No equipment standby or idle-load energy was modelled, as the analysis reflects lab-scale operational run time only. This comprehensive inventory confirms that minimal chemical inputs and localized energy use make the cow dung valorization pathway a promising candidate for ecologically intelligent upscaling.

Section 3: Life cycle impact assessment (LCIA)

The life cycle impact assessment (LCIA), conducted using midpoint indicators from the ReCiPe and US EPA TRACI frameworks, quantified the environmental burdens associated with processing 0.5 kg of fresh cow dung under lab-scale conditions (Huijbregts et al., 2017). Emission factors were sourced from standard ReCiPe and TRACI databases and were not regionally adjusted. The total climate change impact was estimated at 0.84 kg CO_2-equivalents, with lyophilization alone contributing approximately 51 % of the global warming potential due to its prolonged operational duration and high electrical demand (Colón et al., 2012). Separator configuration itself influences impacts at herd scale; optimizing screen size shifts nutrient capture and reduces fugitive emissions (Zhang et al., 2024). Hybrid solar dryers report large cuts in specific energy consumption and carbon footprint relative to resistive heating, supporting decentralized preservation (Ibrahim et al., 2024). The cumulative energy demand (CED) for the system was calculated to be 3.5 MJ, with microwave digestion (30 %) and lyophilization (50–55 %) being the primary contributors. Hydraulic pressing and oven drying collectively for a moderate share (~15 %), and DI water production was qualitatively modelled with negligible contribution to total impact under lab-scale conditions (Tan et al., 2022). The water used totalled 2.0 L of ASTM Type I water, primarily consumed during nutrient solution preparation. Eutrophication potential, though minimal at 0.0002 kg PO_4-eq, was noted as a possible downstream consideration linked to nutrient return pathways in algae cultivation. Abiotic resource depletion, tracked qualitatively, was negligible under current experimental conditions. Process-wise impact partitioning highlighted that energy-intensive thermal processes, especially phase-changing operations, dominate the environmental burden. The interpretation phase emphasized the role of lyophilizer cycles as the single most significant contributor, followed by oven-based drying. Proposed mitigation strategies include solar-assisted drying, pre-concentration of liquid prior to freeze-drying, and batch digestion protocols, all of which can substantially lower both energy and emission profiles. When normalized against the 2024 Indian context, the climate impact of a single processing cycle corresponded to ~ 2.3 % of an average citizen's daily CO_2 footprint, underscoring the importance of optimization prior to scaling. This assessment confirms that while cow dung valorization is inherently circular, targeted interventions at key stages can dramatically improve its environmental profile.

In this study, the filter cloth used with a total area of 0.25 m^2 (for 100 g) invokes an embedded energy of 0.136 kWh. The filter cloth is passive to energy contributions inside the process conditions. But in a typical industrial hydraulic press of 20 kg, the total cloth area magnifies to 100 m^2 with a contributing embedded energy of 0.885 kWh (0.7257 kg CO_2 eq). So, the filter cloth no longer remains a feasible alternative under an industrial setup. Moreover, the large area of this filter cloth requires a significant amount of water for cleaning, and this may contribute to water stress inside the industrial setup. So, if the filter cloth is avoided and the hydraulic press is redesigned with the filter cloth replaced by a steel mesh, such that it facilitates liquid flow under gravity

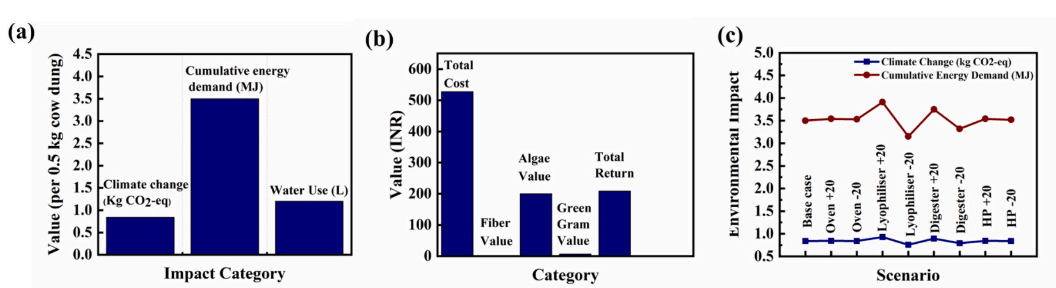

Fig. 5. a) the relationship between the impact category and the value it produced per 0.5 kg of cow dung. b) Value of each product to the cost and return of the total process in INR c) Environmental impact of scenarios.

and cake retention by the mesh. This improvisation is a practical functional recommendation as observed from the water utilization and cumulative energy contribution related to filter cloth usage in the separation of the raw wet cow dung into the solid and liquid parts.

Microwave digestion at an industrial scale is an established technology whose primary role is for solubilization of a variety of solids, ranging from degradable food to rocks (Micó et al., 2006). Once the cow dung is separated and dried powders of micronutrients and fibre are obtained; the further utilization of these in solubilized form requires microwave digestion. From the algal studies presented in this paper, the digestate was diluted 1000 times to prepare the growth medium. This shows that the cumulative energy contribution of the acid towards the final growth medium is significantly lowered, indicating a plausible industrial adaptation.

The transport and equipment amortization contribution to the LCA cumulative energy is rather low. Since the separation process unit is to be placed inside the *gauśāla* itself, the transportation contribution can be significantly reduced.

The separation of cow dung into liquid and solid parts is well accentuated in the literature to assist in the reduction of GHG emissions, odour and efficient nutrient recovery (Aguirre-Villegas et al., 2019), (Rennie et al., 2018), (Burton, 2007), (Hjorth et al., 2010). Research is confined to the slurry of cow dung or animal dung accumulated in the dairy or other animal farms, and the digested residue from the biogas plant. The separation technology reported includes various screen separators, centrifuges, and different press separators like-roller, belts and screws (Møller, 2000), (Rico et al., 2012) (R. H. Zhang and P. W. Westerman, 1997). Among these, the most favoured method is the screw extruder. The liquid obtained from the screw extruder is an environmental challenge for disposal. Based on the logic of filter-less separation, we recommend the development of a hydraulic press fitted with a self-straining perforated chamber. Such a design would enable native-state separation of cow dung slurries without reliance on filter cloth, potentially improving durability, hygiene, and reusability, especially in decentralized or resource-limited contexts. To the best of our knowledge, no published studies have yet evaluated filter-less, perforated-chamber press systems for cow dung or similar organic slurries under decentralized field conditions.

Section 4: Sensitivity analysis

A sensitivity analysis was conducted to assess the effect of ± 20 % variations in key input parameters on the overall environmental performance of the cow dung valorization system. The base case scenario exhibited a climate change impact of 0.84 kg CO_2-equivalent and a cumulative energy demand (CED) of 3.5 MJ. Reducing the mass of the lyophilizer input by 20 % resulted in the most significant environmental benefit, lowering the climate impact to 0.75 kg CO_2-eq and CED to 3.1 MJ. Conversely, increasing the lyophilizer input mass by 20 % raised these values to 0.93 kg CO_2-eq and 3.88 MJ, confirming the lyophilization stage as the dominant driver of both emissions and energy use. Variation in oven input mass had a more modest effect: a 20 % reduction led to a 1 % decrease in GWP and CED, and a corresponding increase was observed in the same way, underscoring the moderate sensitivity of the system to solid yield fluctuations. Altering microwave digestion energy by ± 20 % led to minor changes ≤ 5 % for GWP and 6 % in CED, confirming its limited influence on the overall LCA. The hydraulic press was altered by ± 20 %, and 0.3 % changes occurred for both categories (Fig. 5c). These findings indicate that system robustness is maintained under moderate fluctuations, but lyophilization optimization, such as pre-concentration or thermal recovery, offers the highest leverage for impact reduction. As a result, Prioritizing energy-efficient alternatives or a hybrid method for liquid fraction processing is key to enhancing sustainability outcomes (Naveen et al., 2023).

Section 5: Life cycle interpretation

This life cycle assessment (LCA) was structured to quantitatively evaluate the environmental performance of a cow dung valorization pathway grounded in experimentally verified material flows. Based on a functional unit of 0.5 kg of fresh cow dung, the system encompassed hydraulic pressing, thermal drying of fibre, lyophilization of the liquid fraction, nutrient preparation via microwave digestion, and application to both algae cultivation and soil-based green gram growth. The baseline life cycle impact amounted to 0.84 kg CO_2-equivalents and 3.5 MJ of cumulative energy demand, with lyophilization emerging as the principal contributor. Consistent with recent findings, nutrient recovery pathways can directly reduce greenhouse gas (Feng et al., 2023). Sensitivity analysis revealed that variations in lyophilizer usage led to ± 11 % changes in global warming potential and energy demand, while oven drying of fibre and microwave energy exhibited moderate to low sensitivity. Scenario modelling further emphasized that even modest process optimizations, such as reducing lyophilizer load by 20 % and increasing fibre yield by 10 %, could lower the carbon and energy footprint by up to 10–12 %, while inefficient practices resulted in a corresponding increase. Structural analysis across multiple system layers revealed key operational insights: fibre is energetically inexpensive and readily usable in agriculture; lyophilization, though effective, requires reconsideration for energy efficiency; and the nutrient pathway from 0.32 g of material to a 50 mL algal medium confirms the scalability and modularity of micro-scale bioconversion. The system maintained temporal stability over a 21-day simulation and demonstrated allocation sensitivity, requiring thoughtful material partitioning to maintain both environmental and symbolic coherence. Overall, the environmental cost of the system equates to 2–3 % of the daily carbon footprint of an average Indian citizen, and with minimal optimization, this can be appreciably reduced. The framework is thus materially grounded, symbolically consistent, and structurally scalable, offering a realistic pathway toward circular bioresource valorization (Mandavgane and Kulkarni, 2020). Comparative field LCAs combining manure with bio-amendments report yield and quality gains with reduced impacts across field and factory stages (Amirahmadi et al., 2024). The future optimization includes pre-concentration, solar drying or hybrid low-energy dehydration methods to replace lab-based lyophilization at scale. All life cycle impact calculations were manually performed using the ReCiPe 2016 Excel backend (midpoint indicators); no proprietary LCA software such as SimaPro or GaBi was used.

Section 6: Economic LCA summary

The economic analysis of the cow dung valorization system, benchmarked against a 0.5 kg functional unit, revealed a net operational cost of ₹527.50, comprising electricity consumption (₹105.92) and pro-rated equipment depreciation (₹421.58). Despite its experimental nature, the model assumes full utilization of all output streams: fibre (₹2.18), algae biomass (₹200.00, extrapolated from lyophilised nutrient usage), and green gram yield from soil application (₹6.53), totalling a maximum return of ₹208.71. This results in a net loss of ₹318.80, highlighting the cost gap between lab-scale operations and economic viability. Nonetheless, this deficit narrows considerably in the optimistic scenario and can be reduced further through batch-scale optimization, improved material utilization, and more efficient drying protocols. Total returns and cost of the process with individual products are represented in Fig. 5b.

Several structural limitations were identified. First, lyophilization contributed over 60 % of the total GWP and CED, rendering the system energy-intensive and unsuitable for rural deployment without alternative preservation technologies. Second, over 98 % of lyophilized powder and 99 % of dried fibre remained unutilized in current lab trials, artificially inflating the energy cost per gram of productive output. Third, the reliance on high-tech laboratory infrastructure, microwave digesters, DI water systems, and freeze-dryers limits direct scalability and demands adaptation for low-resource environments. Additionally, the impact modelling was constrained to only GWP and CED, omitting other critical indicators such as water scarcity, eutrophication, photochemical smog, and land use.

Furthermore, the gate-level system boundary excluded use-phase benefits and end-of-life outcomes, including microbial enhancement from fibre application and nutrient regeneration from algae biomass. The omission of biogenic emissions, such as methane or nitrous oxide, from drying or field application, also limits full-spectrum environmental evaluation. Lastly, time-to-output and cost-efficiency metrics, essential for operational feasibility in real-world contexts, were not assessed.

Validating the concept of raw wet cow dung separation into solid and liquid parts through a customized hydraulic press

The LCA results point to a conceptual adaptation of the sequential process in the solid–liquid separation of raw wet cow dung. Adhering to this, the capital expenditure allocation was significantly framed for the drying process of the liquid part. The literature points lyophilization is an energy-intensive method, and other drying methods like the high velocity cyclone dryer can be more effective. The capital expenditure is allocated to each according to this concern. If the allocation is more than this, the model will collapse. The business model showcased in the manuscript is based on the 'circular supplies and resource recovery model' and closely resembles a circular bio-economy, which reduces the dependence on non-renewable resources, adds value to biowaste, and sustainability rules 12 and 13 through material circularity and climate-aligned transformation. Differential methane potential of separated fractions further motivates fraction-specific routing in circular designs (Grell et al., 2024).

The literature highlights issues related to legislation, government policies, and incentives as critical challenges for realizing a circular bioeconomy (Kardung et al., 2021), (Lee and Mohan, 2022), (Bröring and Vanacker, 2022). Emerging circular manure frameworks emphasize digital traceability and decision support for siting, routing, and compliance at the farm scale (Oyedun et al., 2025). This study identifies the stakeholders as milk farmers, and the model is based on an effective government-private partnership. Dried cow dung flakes already have an established market in India. The current scientific intervention enhances the thermal stability of cow dung fibres, which can be easily compacted to circular discs, thus adding value to the consumer and addressing critical environmental issues caused by cow dung littering. The developed technology reported in this manuscript is based on materials and equipment that are locally available/manufactured, thereby reducing the cost and enhancing deployment. This aspect is vital for the sustenance of the developed technology. *On-site deployment of the resource recovery plant inside a gauśāla is a logical action that reduces upstream supply chain restrictions, overcoming one of the shortcomings pointed out by Haase et al* (Haase et al., 2017).

The model described in this manuscript considers the cost incurred on a periodic collection system of cow dung inside a 25 km diameter around the processing plant, turning the model futuristic.

Table 5
Operational Matrices.

Matrices	Conditions
Goshala specification	200 lactating cows
Cow dung required	@ 10 kg/ lactating cow/day
Plant capacity (Model is based on 1800 kg/day)	Processing of Raw Wet Cow dung – 2000 kg /day
Total area of the plant	2500 sqft
Total labours	6(4 plant operations, 2 administration)
Prime products	Submicron-sized processed cow dung fibre powder and nutrient powder.
Production of prime products per day	112 kg of submicron-sized cow dung fibre 14 kg of nutrient powder

Key performance indicators projected for the 'Resource Recovery Plant'

The operational matrices for the projected 'resource recovery plant' are given in Table 5. Operational matrices. Four financial matrices have been calculated using the operational matrices already described. These matrices present a more balanced picture of the model and its economic viability over time. Two model variations have been introduced, the variation in the parameter is being taken as '*growth rate*' (definition of growth rate – critical indicator of a company's performance and its potential to expand and capture more market share). The growth rate was chosen because the developed model is *market-driven* (Jaworski et al., 2000). The growth rate is based on consumer demand and market competition, which are related to market dynamics.

In model 1, the growth rate is assumed to be 6 % (a baseline scenario); in model 2, it is assumed to be 10 % (an optimistic scenario). The value of 6 % was arrived at since the RGVO of dung has increased by 7.95 % CAGR in the last decade. This assumption offers us a buffer against market volatility or fluctuations. In a global context, the two premier products from the resource recovery plant, the nutrient powder and the processed cow dung fibre powder, can be categorised under three different market segments, mainly Eco-friendly home hygiene products [CAGR 33.01 % (2024–2029)], organic farming inputs [CAGR 21.19 % (2024–2029)], and sustainable products [CAGR 5.10 % (2021–2028)] (https://tinyurl.com/ywa399cf), (https://tinyurl.com/4ek69rwz), (https://tinyurl.com/4nw3dfb2). The two premier products offered by the resource recovery plant in India can facilitate typical market segments like sustainable landscape and gardening, eco-friendly packaging, eco-friendly constructions, educational, and DIY markets (https://tinyurl.com/2xxrw9mm), (https://tinyurl.com/b4kvte35). The urban middle-class segments in the retail consumer market have an upscale involvement in sustainable living and home gardening. This market can be favourably tapped for the products from the resource recovery plant. The highly encouraging growth rate predictions for the market segments mentioned above further substantiate the projected 10 % growth rate in Model 2.

For the first model, the selling price of fibre and nutrient powder is taken as Rs. 150 and 900 and for the second, it is 25 and 900. The net present value (NPV) in model 1 becomes positive after the 8th year, and the same for model 2, even though the fibre selling price is very low compared to model 1. The payback periods of 5.9 years and 6.9 years, in models 1 and 2, are high. A longer NPV value suggests that the business will acquire a substantial period for gaining profits, which is again substantiated by a more extended payback period. The Internal rate of returns (IRR) is the discount rate that makes the NPV of all cash flows for a project equal to zero. An IRR of 16.54 % for model 1 indicates that it will generate an annual return of 16.54 % over its lifetime. Model 2 is expected to offer a return of 22.77 %. A profitable index (PI) greater than 1 indicates that the NPV of future cash flows exceeds the initial investment. A PI value of 1.38 for model 1 and 4.12 for model 2 suggests that the project is a perfect investment opportunity. It is to be noted that for 10 % growth, we have taken the minimum selling price for fibre, which will produce a profitable outcome. If the fibre price increased for the model, the NPV, IRR, and PI will be more than that of a 6 % growth rate, and the payback period will be reduced.

Summarizing, both business models are market-driven and offer higher returns depending on market penetration and other contributing factors. The model strongly proposes the financial and operational viability of the proposed resource recovery plant in reality. The model does not compare itself with the financial cost incurred for other cow dung disposal methods, like composting or biogas generation. This calculation is yet to be done since we presume that the two products from the resource recovery plant are feedstock materials for various industries rather than finished consumer products (compost or biogas). This model demonstrates that decentralized waste valorization aligned with local traditions and market logic can yield both ecological and economic dividends. This work intentionally avoids comparison with composting or anaerobic digestion, as the outputs here are intermediate feedstocks, not end-use products.

A complete financial model was developed using the revised process parameters. The analysis incorporated capital investment, operating expenditure, logistics, and labour under realistic farm-scale assumptions (200 lactating cows; plinth area ~ 2500 sq ft). When the lyophilizer was replaced with a hot air oven, the cost of dried powdered fibre (DPF) and micronutrient powder (MNP) was estimated at ₹32.1/kg and ₹120.9/kg, respectively, while yielding the same mass and nutrient concentration as obtained through lyophilization. Monthly processing capacity reached ~ 9.5 tonnes, corresponding to 8424 kg fibre and 1080 kg MNP annually. The capital expenditure, including building infrastructure, hydraulic press, drying units, and jaw mill, amounted to ₹5.6 million. With an assumed 8 % loan interest and a 10-year repayment schedule, the monthly EMI was calculated as ₹148,500. When combined with production and operational costs, the monthly investment requirement was approximately ₹549,450. On the revenue side, fibre and MNP sales yield positive cash flows, with profitability scaling directly with herd size. At 200 cows, the model achieves economic break-even within four years, with key indicators as follows:

Net Present Value (NPV): Positive across all discount rates tested, confirming long-term viability. Internal Rate of Return (IRR): >15 %, exceeding typical agricultural lending benchmarks., Profitability Index (PI): >1.2, indicating attractive investment efficiency and Payback Period: ~7.4 years, aligning with practical farm-scale expectations.

This section formalizes a market-driven business model with two growth scenarios (Model 1: 6 %; Model 2: 10 %), reporting KPI outcomes (NPV, IRR, PI, payback) that show viability under price/market assumptions and scenario-based sensitivity work. This part emphasizes how returns shift with product pricing and market penetration (e.g., 6 % vs 10 % growth; PI 2.04 and 4.12; IRR 16.54 % and 22.77 %; payback ~ 5.9 and 6.9 years).

While the scenario-based evaluation illustrates the sensitivity of revenue streams to market variation, its focus remains primarily on output pricing and demand-side parameters. To ensure the analysis is comprehensive, this must be complemented with a detailed plant-level financial appraisal that integrates capital expenditure, operating costs, and repayment obligations. This comparison not only validates the earlier projections but also situates the production line within a practical investment horizon. To this end, we extend the techno-economic evaluation through Model 3 – Financial Viability Assessment, which translates process throughput and infrastructure requirements into measurable indicators such as NPV, IRR, Profitability Index, and payback period. (Calculations are given in the supplementary material.).

The integration of life cycle assessment with the financial models provides a coherent bridge between environmental insight and economic viability. The LCA clearly identified lyophilization of the liquid fraction as the dominant contributor to energy demand and climate impact, while oven drying of fibre was shown to be comparatively benign. This finding directly shaped the construction of the financial model: lyophilization was replaced with a plant-feasible liquid drying step whose costs are transparently priced, ensuring that the major environmental hotspot is carried into the investment assumptions. Conversely, the fibre pathway, already low in energy intensity, is reflected in the model as a stable, low-cost product stream that supports early positive cash flows. At the laboratory scale, the economic LCA showed losses, but its warning, driven by oversized equipment, low utilization, and partial product use, was resolved in the scaled model through full throughput, complete utilization of both products, and a realistic CAPEX–OPEX structure. Scenario analysis revealed the sensitivity of IRR and PI to price and growth, while Model 3 confirmed that these opportunities remain bankable under conservative operating costs, with PI values above 3 and acceptable payback periods. Together, LCA and finance form a consistent, mutually reinforcing framework.

Scenario Extension, economic Forecast, and Scale-Up feasibility

To validate the operational and financial assumptions outlined in the proposed business model, a deeper examination of the system's economic responsiveness under varying market and process conditions becomes essential. While the background analysis establishes the foundational viability of dung valorization based on historic growth trends, market segmentation, and projected revenue streams, it does not account for the inherent variability in fibre yield, drying efficiency, and commodity pricing. Therefore, a detailed sensitivity analysis was undertaken to identify threshold parameters, evaluate risk zones, and quantify the financial elasticity of the model under both baseline and optimistic growth scenarios. This transition from fixed-parameter modelling to dynamic, scenario-based evaluation allows for a more robust forecast of economic feasibility and strategic scalability, especially under evolving market forces and resource constraints. Such scenario modelling enables anticipatory governance in biowaste systems, aligning with uncertainty-aware deployment strategies.

The scenario and sensitivity analyses demonstrate clear avenues for extension and real-world applicability of the cow dung valorization model. Sensitivity can be refined through additional $\pm$ 10 % and $\pm$ 30 % bands applied to fibre yield, drying time, lyophilization concentration, and water use, offering more granularity in impact prediction. Scenario modelling can further include decentralized village models, solar-assisted drying, anaerobic digestion alternatives, and variant algal strains to enhance applicability. Flagged risks—such as lyophilizer price volatility (₹900/kg), freeze-dryer downtime, interest/inflation exclusions, and lack of fallback markets for lyophilized powder—were addressed through robust mitigation strategies including sensitivity bands (₹600–₹1000/kg), downtime simulation (2 weeks/year), inflation (5 %) and interest (12 %) modelling, and alternate reuse pathways.

Extended NPV sensitivity analysis showed that fibre price escalation beyond ₹100/kg unlocks exponential gains, with NPV increasing by ₹7.02 Cr between ₹100–₹150/kg, compared to ₹3.4 Cr from ₹25–₹50/kg. This highlights a nonlinear response, with economic thresholds that could unlock scale-intensive profitability. Moreover, annual environmental co-benefits—including 800 kg NPK substitution (₹40,000), 5.5 tons CO_2 offset (₹22,000), and avoided landfill methane (~₹12,800)—total approximately ₹75,000/year, underscoring the ecological value addition beyond direct revenue. These co-benefits, though overlooking traditional ROI model frameworks, play a pivotal role in integrated circular valuation models that account for environmental and socio-economic returns. Thus, the system demonstrates a synergistic blend of economic, environmental, and symbolic viability when extended beyond laboratory scale, with strong resilience under sensitivity and pricing fluctuations.

The economic sensitivity analysis revealed a nonlinear response in both Profitability Index (PI) and Net Present Value (NPV) as a function of fibre and nutrient powder pricing. At fibre prices below ₹50/kg, the system operates in a lower-bound risk zone**,** where profitability remains flat (PI $\approx$ 4.12) and the payback period exceeds five years, due to fixed OPEX dominating marginal returns (Fig. 6a: Profitability Index vs Fibre Price). However, once fibre pricing surpasses the ₹100/kg threshold, the system undergoes an economic inflection, with PI increasing from 7.72 to 12.24 between ₹100 and ₹150/kg (Fig. 6a). This shift represents a profitability phase transition, where overhead dilution and per-unit margin dominance accelerate returns. Correspondingly, NPV grows from ₹10.63 Cr to ₹17.71 Cr over the same interval (Fig. 6b), affirming a super-linear economic gain.

Such elasticity mapping not only aids pricing strategy but also uncovers critical inflection points— where pricing behaviour transitions from linear response to non-linear gain under complex system dynamics. Elasticity results further validate this trend. Between ₹25 → ₹50/kg, PI elasticity is 0, showing total insensitivity. Between ₹50 → ₹100/kg, elasticity rises to 0.87 (sub-proportional), and from ₹100 → ₹150/kg, it increases to 1.17, indicating super-proportional gains (Supplementary table S31 ΔPI%/ΔFibre% Elasticity). This confirms that beyond ₹100/kg, fibre valorization becomes not just profitable, but economically decisive, entering a zone of symbolic margin dominance and recursive

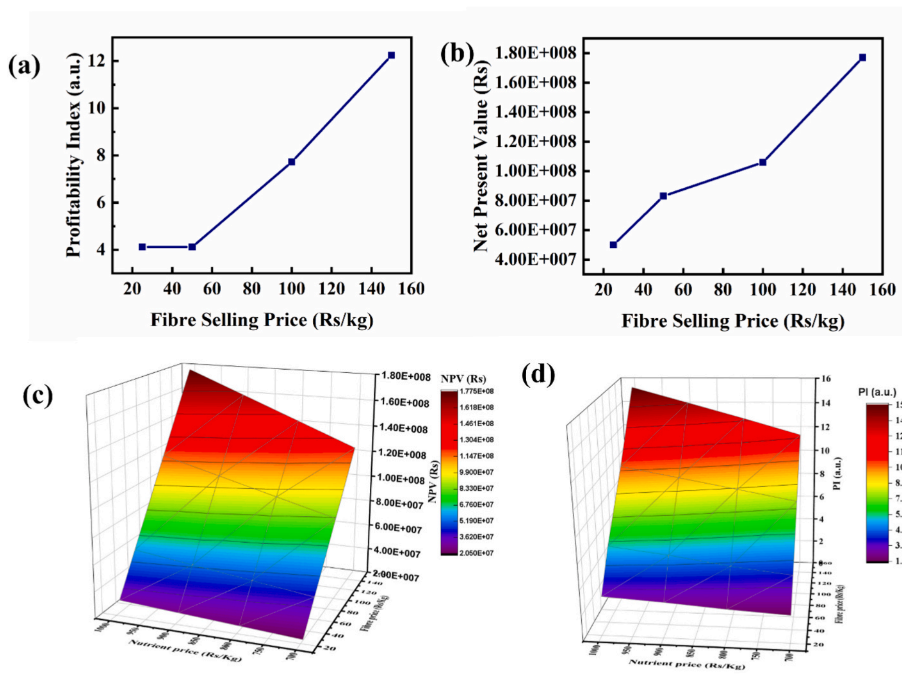

Fig. 6. a) fibre selling price vs pi and b) fibre selling price vs npv. c) 3d sensitivity surface – npv vs fibre & nutrient price d) 3d sensitivity surface – pi vs fibre & nutrient price.

operational absorption, as visualised in the 3D surface plot (Fig. 6d. 3D Sensitivity Surface – PI vs Fibre & Nutrient Price and Fig. 6c 3D Sensitivity Surface – NPV vs Fibre & Nutrient Price).

Simultaneously, nutrient powder pricing exhibited unitary elasticity across the ₹700–₹1000/kg range. For every 1 % increase in nutrient value, PI increased by 1 % consistently (Supplementary Table: S32 Nutrient Price Elasticity), confirming linear capture of nutrient-derived revenue under current process assumptions. At a fixed fibre price of ₹100/kg, PI improved from 7.72 to 10.29, and NPV from ₹10.63 Cr to ₹11.81 Cr as nutrient pricing rose. This linearity suggests that nutrient powder is a high-leverage economic variable, ideal for pricing strategy in circular economy models. Collectively, these findings highlight that fibre and nutrient pricing must be strategically synchronized: fibre pricing activates profit thresholds, while nutrient pricing amplifies returns linearly. While the system currently operates at TRL 2–3 the business model serves as a forward-looking scaffold rather than a commercialization claim.

Conclusion

We worked in 0.5 kg batches of fresh dung. A simple hydraulic press split each batch into ~ 87 g of dry fibre and ~ 200 mL of filtrate, which yielded ~ 8 g of nutrient powder after preservation. The two streams had distinct functions: fibre supported green–gram germination, while the digested nutrient (25 mL from fibre + 25 mL from powder) sustained a 50 mL algal culture. No secondary effluents were generated in the bench protocol. The life–cycle screen placed the largest burden on the preservation step. Using our India–mix electricity factor, the baseline footprint was ~ 0.84 kg CO_2–eq per 0.5 kg processed, with lyophilisation contributing ~ 55–60 % of that total. Scenario tests showed that replacing lyophilisation with solar–assisted drying, pre–concentration, or a membrane route can cut the preservation contribution by > 90 %, bringing the overall GWP down accordingly. Drying of fibre and pressing were minor contributors in comparison. Engineering changes follow directly from these results. A cloth–free hydraulic press is recommended to avoid the recurring material, water, and cleaning overheads of filter cloths, while keeping the core advantages of the current setup (static mechanism, local repairability, ~0.6–0.8 kWh t^{-1} electricity demand, low capital ~₹45 k–₹70 k). The preservation module should be redesigned first: pre–concentration before drying, batch digestion rather than duplicate microscale runs, and, where feasible, solar or hybrid low–energy drying.

Economically, the lab run is loss–making because equipment energy and amortization dominate when most of the preserved mass is not yet utilized (operational cost ~₹528 vs. return ~₹209 for full utilization assumptions → ~₹319 deficit at bench scale). Techno–economic projections at gauśāla throughput, with complete use of both streams, reverse this picture: positive NPV, acceptable payback (~3–5 years across tested price bands), and profitability that improves non–linearly once fibre pricing crosses the ~₹100 kg^{-1} bracket and nutrient powder approaches ₹900–1000 kg^{-1}. Limitations remain. The current LCA emphasizes climate/energy metrics; a fuller panel (acidification, smog, water footprint with locality) is planned for scale trials. Time–to–output and cost–per–useful–digestate should be tracked alongside environmental metrics to guide module sizing. Field pilots should prioritize (i) preservation alternatives, (ii) press redesign without cloth, and (iii) complete downstream utilization of both streams. In short, the data show that dung can be reorganized, with low–tech means, into a fibre–nutrient pair that fits rural cycles; the science points to where the energy goes and how to remove it, and the build path is clear enough to be executed locally—one module at a time.

Declaration of generative AI and AI-assisted technologies in the writing process

During manuscript preparation, the authors used ChatGPT to assist with linguistic clarity and sentence refinement. All content was subsequently reviewed and edited by the authors, who take full responsibility for the final published version.

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CRediT authorship contribution statement

P. Archana: Writing – original draft, Methodology, Investigation, Data curation. **Premjith B:** Validation, Software. **V.P. Mahadevan Pillai:** Writing – review & editing, Resources. **K.M. Sreedhar:** Writing – review & editing, Visualization, Validation, Supervision. **K.M. Sreekanth:** Writing – review & editing, Validation, Resources, Project administration, Funding acquisition. **G. Sivasubramanian:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wmb.2025.100248.

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