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Waste-to-Value Innovation in the Pet Care Industry: Transforming Soybean By-Products into Sustainable Cat Litter

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Abstract:
This paper analyzes the viability of valorising a by-product of tofu/soybeverage okara, a significant by-product named Mr. Okara, as a new cat litter material as part of a waste-to-value system and a circular economy. The review of evidence summarises the data on the composition of residues (high initial moisture fibre-rich and protein-rich), processing routes needed to stabilize the product (drying, particle-size control, granulation, and hygiene protection), and functional performance expectations, such as the absorption and liquid retention, clumping stability, and dust ability. Compared to mineral litters, the residue-based systems have a potential to lessen reliance on extractive input and allow landfill diversion although net sustainability benefits will be dependent on energy efficient drying and feasible end-of-life treatment of biologically contaminated used litter. Life-cycle considerations are referred to define major motivators of carbon footprint and resource efficiency such as allocation options of by-product load and scenario sensitivity across disposal paths. The implications of the industry are presented in terms of scalable sourcing in and about soy-processing hubs, quality-control requirements to handle variability of feedstock, and economic logic of prevented residue disposal and possible differentiation of products. Altogether, soybean residue demonstrates plausible prospects as a bio-based litter substrate in case the processing is optimized to match the safety and performance criteria without compromising a positive environmental image of the sustainability-focused pet care markets (Oyedeji et al., 2024; Karim et al., 2025; Aduba et al., 2025).

Keywords: Soybean residue (okara) Cat litter materials, Waste-to-value, Circular economy, Life-cycle assessment, Sustainable pet care products.

1. INTRODUCTION

The worldwide expansion of the global growth of soybean-based food production has been significantly increased in recent years due to the demand for plant-based alternatives in the food industry. As a result, large amounts of by-products are produced during the manufacture of products from soybeans, such as tofu and soy milk. These by-products, also mainly soybean residue, are frequently disposed in waste. However, with the recent interest growing in sustainability around the world, there is an increasingly growing focus on finding innovative ways to repurpose these by-products. Soybean residue is high in fibre and proteins and has a great potential to be a resource in many different applications, especially in industries such as pet care (Oyedeji et al., 2024).

Food-processing wastes, especially those from plant-based industries, are remarkable environmental problems. The disposal of these by-products generally involves landfilling or incineration, both of which have a detrimental effect on the environment. Landfilling these residues consumes precious space in already overstretched waste disposal systems and the incineration process results in the release of harmful pollutants into the atmosphere. Furthermore, such a practice is responsible for the destruction of some precious items which can be repurposed in creating some environment-friendly products. The environmental consequences of such methods of waste disposal require innovative ways to manage these by-products in a more sustainable way and thus ensure that these by-products contribute positively to the circular economy.

The need for sustainable materials in the pet care industry, and in the case of cat litter, has been steadily growing. Traditional cat litters, which are made mostly from clay or silica, have been a cause for concern because of its impact on the environment. The mining of clay for the manufacture of cat litter contributes to habitat destruction, and these products, which are not biodegradable, cause a large amount of waste in landfills. This expansion in the need for sustainable materials for pet care is a potential chance to investigate alternative and eco-friendly pet care materials that are both functional and environmentally responsible (Thomas et al., 2024); for instance, soybean-based materials. Soybean residue with its potential to absorb moisture and neutralize odours could be a good alternative to conventional cat litter materials.

The objective of this research is to study the potential of soybean residue, tofu by-products to be functional and sustainable cat litter material. This study attempts to assess the material characteristics of soybean residue in terms of the absorption capacity, clumping performance and the environmental impact of the material, as well as the feasibility of the processing of soybean residue into a product that would have commercial appeal. By tackling the lack of sustainable materials for the pet care industry, this research seeks to provide a contribution to the development of a more environmentally friendly cat litter alternative, which is in line with wider objectives of waste valorisation and sustainable resource management (Aduba et al., 2025).

2. SOYBEAN RESIDUE (TOFU BY-PRODUCT) CHARACTERISTICS

Soybean residue especially tofu by-products are valuable material which has been disregarded in industrial application. This by-product is made up of mostly fibrous plant material that is left over after soybean milk extraction in tofu making. The composition of soybean residue of high concentration of dietary fibre, proteins, and moisture content makes it an interesting candidate for different applications, including absorption-based applications such as cat litter. The fibre content of soybean residue consists mostly of cellulose and hemicellulose; both of which are known for their capacity to retain moisture and to provide structural integrity, important properties for the application of absorption (Karim et al., 2025). Additionally, the protein content which is left after extracting the soybean oil and milk further contributes to its value as a high value bioproduct.

The moisture content of soybean residue usually varies between 50-70%, depending on the processing conditions as well as the particular by-product. This high moisture content can pose challenges in terms of storage and transport, as this high moisture level can favour the growth of microorganisms and the decomposition of the product. However, by the use of suitable drying methods, soybean residue can be converted into a more stable and functional material, which can be used for pet care products such as cat litter (Karim et al., 2025). This moisture retaining ability is one of the reasons that soybean residue holds potential as a potential moisture absorbing material which is able to effectively trap and hold liquids, a very important property for a successful cat litter material.

Soybean residue disposal is not ideal currently despite its potential. In many places of the world, tofu by-products are discarded as waste, either by being placed in a landfill or incinerated. These disposal methods add to environmental pollution, as both landfilling and incineration of waste add to the emission of greenhouse gases and other pollutants into the environment. In addition, when soybean residue is taken to landfills, it is not broken down efficiently as it often contains preservatives or other chemicals which reduce their biodegradability (Sanchez-Hernandez & Megharaj, 2024). These disposal practices not only waste a valuable resource, they also contribute to the depletion of natural resources through the production of waste. The environmental consequences of such disposal methods are a key reason why alternatives or sustainable solutions to convert the food processing residue such as soybean residue into valuable products are in demand.

The potential benefits of soybean residue for use in applications that require absorption, such as cat litter, are great. The characteristic moisture absorbing characteristics of soybean residue make it an ideal choice as cat litter materials. Soybean residue's fibre structure and high surface area provide it with high efficiency for the trapping of liquids and odours, which are key characteristics for any good cat litter product. In addition, the material is biodegradable, non-toxic and ultimately more sustainable than traditional cat litter made with clay or silica. Soybean-based cat litter could present a sustainable alternative that could support reducing the environmental impact of pet care products, while also providing the same or even better performance as traditional pet care products (Jha & Nandulal, 2023).
Soybean residue is also an environmentally friendly alternative in terms of production. Unlike mineral-based cat litter, which involves mining and the use of a lot of energy to produce, soybean residue is a by-product of the tofu-making process and will be plentiful and cheap, most of the time. By using this waste product, the pet care industry would be able to greatly reduce its dependency on non-renewable resources while adding to a circular economy. The valorisation of soybean residue is part of efforts made elsewhere in the world to minimise food waste and minimise the environmental footprint of consumer products (Jha & Nandulal, 2023). The ability to take something that would normally be treated as waste, and turn it into something that can be turned into a useful and sustainable product, such as cat litter, not only benefits the environment but also helps to create economic opportunities in terms of waste management and product innovation.

3. PROCESSING PATHWAYS TO RESIDUE BASED SOYBEAN CAT LITTER

Transforming the soybean residue (okara) byproduct from production of tofu into a usable cat litter requires a series of stabilization and upgrading processes superior to naturally high levels of moisture, heterogeneous particle structure and tendency of microbial spoilage of the okara. The main technical goal of processing is to transform a wet and biologically active by-product to the dry, hygienic, free flowing granular medium which is able to absorb liquid efficiently, releases little odour and is stable during storage and use. To do this, processing pathways are usually characterised by some combination of moisture reduction, particle engineering (size control and granulation), implementation of additives or treatment steps for Odours and binding performance and safety controls to provide hygienic quality and acceptability to the user (Jančauskas et al., 2023; Jha & Nandulal, 2023).

3.1 Methods of Reducing Moisture and Methods to Improve the Drying Methods

Moisture reduction is the first and the most critical step as the fresh soybean residue has lots of water content which increases the rate of enzymatic degradation and microbial growth. Effective drying provides the chance to stabilize and increase the shelf-life and other subsequent shaping processes such as pelletization. Industrially, drying can be deal with thermal convection drying or by hot air tray or belt drying or hybrid systems which designed energy-efficient. Process selection should be a compromise between energy demand, throughput and product quality - in this case avoiding excessive thermal damage which can result in changes to fibre structure or undesirable odours. From a resource recovery perspective, drying technologies can be analysed also based on principles of energy optimization and process intensification in the same as in the case of valorisation of low-value bio-resources as combustion and/or thermal integration can decrease overall energy penalties (Jančauskas et al., 2023). In practical terms moisture targets need to be defined in order to help with granule integrity and also to limit microbial activity, "optimal" range is a function of binder systems and desired clumping behaviour but the direction is the same, limit water as much as is necessary to stabilize the residue whilst ensuring that there is a functional porosity to ensure absorbency.

3.2 Particle Size/ Granulation Adjustment

After drying process, the residue has to be adjusted in particles to get better on flowability, dust control and consistency of absorption. Raw dried residue may be fibrous and irregular resulting in poor packing behaviour and inconsistent clumping. Controlled particle distribution is possible with the help of milling, sieving and fractionation. This is followed by granulation or pelletization for formation of stable particles of predictable geometry having mechanical strength. Granulation takes the credit for decreased release of dust, improved handling and also controlled absorption of liquids - important usability criteria for litter materials. Approaches to convert agricultural residues into the standardized and particulate end-products has put a focus on mechanical densification and particle engineering in combination with process parameters (e.g. pressure, residence time, conditioning moisture) in order to achieve repeatable material performance (Baskar, 2024). For soybean residue, granulation design will have to place emphasis on the need to maintain the internal pore structure (to provide absorption) and also develop enough external strength to provide protection against crumbling during transport and use of the material.

3.3 Controlling the Odour And Viscosity Binders Improvement

Functional cat litter therefore has to control the odour both physically (= adsorption) as well as chemical/biological (= inhibition of the volatile compounds). Soybean residue can contain residual organics which can contribute to odour formation if not stabilised and processing should be provided with steps to mitigate the formation of odours and enhance odour capture. Odour control strategies can include incorporation of natural adsorbents, pH adjusting agents or binding systems for the reduction of release of ammonia and the stabilisation of volatile components. Binding enhancement is also important especially if clumping performance is a target. Binders are used in order to help increase the durability of the granules, and possibly help the cohesive clumps to form when wetted. Selection of binders ought to take into consideration factors such as safety, biodegradability and end of life effects and performance in situation of repeated wetting. Work on mineral-related functional additives to understand how trace components/material formulations can have an effect on performance results in biological systems and in application contexts are also of importance - principles which are also transferred in litter formulation decisions when optimizing adsorption, binding and stability in actual use situations (e.g. Kumar et al, 2025) In an applied materials sense, formulation development should be set up as a design of experiments problem in which variations of binder type/ratio, conditioning moisture and granulation parameters are varied in order to discover performance/cost/sustainability tradeoned.

3.4. Safety and Hygiene Problems of processing materials

And since soybean residue is an organic substrate, safety and hygiene controls are not an option - that's a basic requirement of any consumer-facing pet care material. Processing therefore has to ensure the microbial contamination is prevented and the finished granules are stable in storage. Hygiene considerations are varied - from handling the incoming material (controlling time/temperature), drying validation (sufficient lethality or reduction of microbes) and storage post processing which require moisture controlled conditions. In addition to this, exposure to dust should be at as low as possible in milling and screening by enclosed systems and proper filtration. From a sustainability viewpoint, the hygienic stabilization also can be discussed as "a preventive measure of waste management: to reduce the losses due to spoilage and ensure that the products that are valorised do not carry new health risks" [Jha and Nandulal, 2023]. Finally, safety assessment should be extended to pet exposure pathways (incidental ingestion, contact with paw etc.) which implies that additives and binders as well as any deodorising agents that have to be used should be chosen for low toxicity and compatibility to animal welfare norms.

Overall robust processing pathway For the soybean residue based cat litters ranges of Drying for Stabilisation, Particle Engineering for Usability, Formulation Strategies for odour and clumping and Hygiene controls for consumer safety. (Jančauskas et al 2023; Baskar 2024; Kumar et al. 2025; Jha & Nandulal 2023). This sequencing has the advantage of taking an organic material which is unstable and converting it to a standardised material which is ready for application testing as well as sustainability testing in further sections.

4. FUNCTIONAL PERFORMANCE EVALUATION

Functional performance is the biggest factor to whether soybean residue-based cat litter is a potential credible alternative to conventional mineral litters. Performance evaluation should be structured as a materials functionality issue, in which absorbency, clumping behaviour, dust propensity and compatibility with the user and environment are all aspects which help to define product acceptability. Since soybean residue is organic and fibre rich substrate, its dynamics in the presence of liquid will be different from the dynamics of mineral matrices, so the performance therefore needs to be evaluated using similar parameters under standardised conditions representing the actual use of the litter box (Oyedeji et al., 2024; Karim et al., 2025).

4.1 Capacity for Absorption and Behaviour of Retaining Liquids

Absorption capacity is the mass or volume of absorbed liquid per unit mass of litter whereas liquid retention is the extent to which absorbed liquid is immobilised devoid of any leakage during handling or loading. In soybean residue systems absorptive ability is dependant to a large extent on the fibre morphology, porosity and surface chemistry. The capillary action of the cellulose-rich structures facilitates a quick wetting degree and uptake of the substance but the level of stable retention is dependent on the resistance of the pore collapsing and the integrity of the network of the granules post wetting (Vasiliauskienė et al., 2023). Practically, for absorption testing we have to consider (i) initial rate of uptake (ii) equilibrium absorbency, (iii) retention for mechanical disturbance, since scooping and pet movement give rise to shear and compression. A major performance risk is a process of over-swelling or breakdown of the structure with repeated wetting, which could have implications on the reusability and increase the fragmentation of the material. Accordingly, functional evaluation has to consider "high absorbency" and "structural robustness" as a coupling properties and not as single targets.

4.2 Clumping Mechanisms of Performance

Clumping performance is important for user's convenience and separation of the waste. In engineered organic litters the clumping often is a result of the combination of (a) binder mediated cohesion, (b) fibre entanglement and (c) moisture triggered interparticle bridging. Soybean residue granules have the ability to be forced into cohesive masses when wetted because of the adhesion between the particles present when the hydrated fibre matrix and any added binders is present. However, clump quality is multi-dimensional: it is made up of clump formation speed, mechanical strength, resistance to crumbling during scooping and minimal adherence to the litter tray. From a waste-to-value perspective, functional clumping also has been associated with processing decisions - particularly granule density, particle size distribution and binder choice etc. that will collectively determine the distribution of water and where cohesion occurs (Oyedeji et al., 2024; Baskar, 2024). A well designed residue based litter should be in discrete stable clumps that have integrity during handling but do not have excessive residual wet patch that may drive odour generation.

4.3 Dust Amount and Dust and Indoor Air Quality Problems

Dust emission is a material handling issue that has the direct impact on indoor air quality and user acceptance. Dust is affected by particle friability, fines, abrasion in transport and mechanical stresses of pouring and digging. Organic residues that are too little and are not granulated well or are too dry and brittle may produce high fines and dry and brittle granules may suffer fracturing. In indoor conditions, airborne particulate matter can be cause of respiratory irritation relevant for human and animal. As such, evaluation of dust should be considered as a performance criterion, as well as absorbency and clumping, and not as a secondary property. Processing strategies in order to reduce fines (screening), increase the particle robustness (densification) and control the surface abrasion (optimized granule hardness) is typically needed in achieving low dust performance profiles (Karim et al., 2025). In the case of comparative testing both "dust released during pouring" and "dust generated after simulated use" can be used as useful endpoints.

4.4 Comparison to Traditional Mineral Based Cat Litter

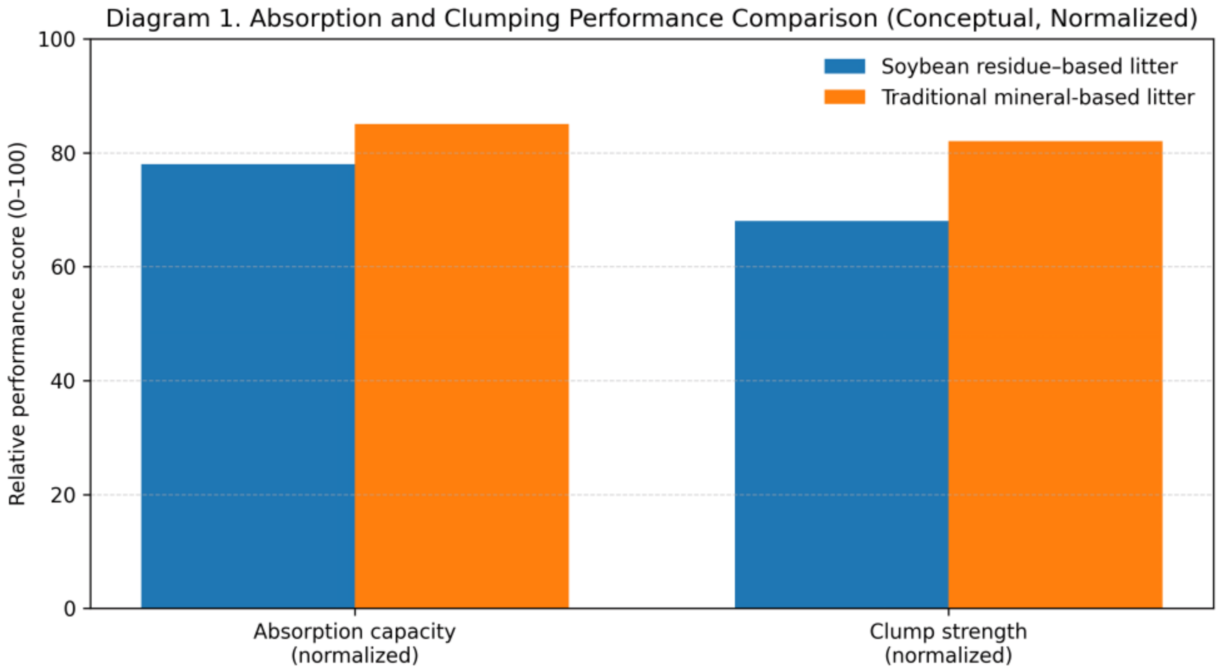
Mineral litters - often being based on clay - have always been the predominant choice because of their strong absorption ability, clumping performance and handling characteristics. However, their performance benefits have to be weighed against environmental issues linked with the extraction as well as the end-of-life disposal. Soybean residue--based litter should therefore be considered from a balanced performance comparison: It does not have to be better than mineral litter in all regard, but should be at least able to fulfill minimum functional necessity values while presenting sustainability values. Comparative evaluation must be made in the areas of absorbency (capacity and retention), clump strength, odour contained, dust propensity and handling by the user. Organic litters can potentially compete with the mineral litters on the biodegradation and the potential landfill diversion but need careful engineering in order to have the mechanical stability and dust control of the mineral litters (Aduba et al., 2025).

Table 1. Comparison of Performance Metrics: Soybean Residue vs. Traditional Cat Litter
(Baskar, 2024; Oyedeji et al., 2024)

Performance metric	Soybean residue–based litter (expected trend)	Traditional mineral-based litter (expected trend)	Evaluation relevance
Absorption capacity	Moderate–high (fibre capillarity)	High (mineral porosity)	Determines urine uptake and surface dryness
Liquid retention	Moderate (depends on granule integrity)	High	Reduces leakage and rewetting
Clumping speed	Moderate–high (binder-dependent)	High	Controls rapid waste isolation
Clump strength	Variable (processing/formulation dependent)	High	Affects scooping losses and breakage
Dust generation	Low–moderate (if well-granulated)	Moderate–high (fines common in some clays)	Indoor air quality and user comfort
Odour containment	Moderate–high (additive/processing dependent)	Moderate–high	Controls ammonia/volatile release
Mechanical durability	Moderate (may degrade with repeated wetting)	High	Impacts lifespan and tracking

Diagram 1 Placement

Diagram 1: Absorption and Clumping Performance Comparison *(Vasiliauskienė et al., 2023)*



5. THE ASSESSMENT ON THE ENVIRONMENT AND SUSTAINABILITY

The best way to assess the sustainability profile of soybean residue-based cat litter is from the lens of systems-thinking and how waste is reduced, resources are efficient and life cycle impacts are reduced from upstream of sourcing to end-of-life management. Different from traditional mineral litters, based on extractive supply chains, that end up in landfill as a persistent stream of solid waste, soybean residue-based litter instead is integrated in a waste-to-value logic, i.e. is based on an existing (food processing) flow and can potentially be re-entered into biological cycles, either via a biodegradation pathway or composting pathway, depending on the extent of contamination and disposal rules in place (Thomas et al., 2024; Aduba et al., 2025). Environmental assessment should therefore not only be a comparison of "product performance", but also go beyond to find out if the material, in deed, reduces the overall burdens in the value chain in a meaningful way.

5.1. Waste Reduction and Resource Efficiency

Soybean residue (okara) is produced in great quantity as a by-product of the production of tofu and soy beverages and it is often handled as low value waste, animal feed or disposed of in landfill where the logistics and regulations limit other applications. Valorisation of this residue in the form of cat litter has the potential to help reduce waste loads to divert organic by-products from disposal channels by the productive use of these organic by-products. From resource efficiency perspective, the approach helps in increasing the utilisation rate of agricultural inputs through accomplishing more functions from the same harvested biomass of soybeans in accordance with the circular bioeconomics (Thomas et al., 2024). However, there are always resource efficiency considerations of processing such that if the energy input of drying and granulation is high, this could reduce the processing net benefit. Therefore, gains in sustainability have to be calculated in terms of balancing the loss of impacts of waste disposal and the amount of energy and materials used in for example the stabilization and manufacture of the litter.

5.2 Issues of Life Cycle of Upcycled Soybean Residue

Environmental impact assessment - Life cycle thinking For the environmental impacts of a product, environmental impacts of collection, transport, preprocessing (drying / milling), granulation / formulation, packaging, distribution, use and at the end of life, a tracing of the environmental impacts must be done. The key differentiator for soybean residue litter is that it is feedstock by-product and so there may be less upstream burdens by comparison to virgin mineral extraction. However, upstream allocation choices are important: environmental accounting should be used to make clear choices on how to distribute the impacts of soybean cultivation and tofu production between primary products and residue streams (Aduba et al., 2025). In the many life cycle frameworks, it is possible to allocate lower burdens to by-products, such that residue valorisation may look particularly good, but such allocation choices should be clearly justified and allocation choices tested on sensitivity for different allocation methods.

End of life also has a material influence. If soybean residue litter is disposed in landfill, it may contribute to impacts of organic decomposition in landfill based on landfill and methane management. If it is composted or treated in controlled systems it may have a more powerful circularity in terms, it returns organic matter back to soils (Aduba et al., 2025). In practical sense litter is likely to be contaminated with animal waste which may limit the composting options and may cause hygienic problems. Thus, the basis for sustainability assessment should not be an ideal end of life situations but the assessment of realistic disposal pathways on a regional basis.

5.3 Carbon Footprint Potential, and Landfill Diversion Potential

Carbon footprint comparisons should include (i) avoided mineral litter inputs extraction and processing, (ii) avoided disposal burdens for soybean residue as well as (iii) added emissions for drying and processing operations. One of the most important environmental levers can be landfill diversion, using soya bean residue in cat litter it's possible to minimise both the amount of waste in the food industry as well as, potentially, the amount of persistent mineral litter that ends up in landfill (Faria et al., 2023). However the scale of this diversion is dependent on the scale of adoption and depending on the consumer disposal behaviour. Where such product allow for increased rates of biodegradable waste management (where and safe) carbon may be enhanced through decreased reliance on landfill and better organic recycling results. On the other hand processing which requires high temperature drying without energy recovery and optimization, the footprint of the manufacturing process can counteract part of the benefits at the upstream (Faria et al., 2023).

Moving Away from the Principles of Circular Economy

The alignment between circular economy and circular economy can be best demonstrated if circular economy system can exhibit material loop closure, waste minimization and value retention. Soybean residue-based litter is circular in nature in that it takes a by-product and turns it into a consumer material that can be used as a substitute for more extractive materials. But, circularity does not happen in an automatic fashion: it needs to be built into the supply chain. This includes making stable sourcing agreements with tofu processors, optimisation of the logistics in order to minimise transport emission and/or the choice of additives/binders that guarantees biodegradability and minimise toxicity issues (Maroušková, 2023). Circularity is also dependent on "downstream compatibility" which refers to if the used product can safely and legally enter composting or other biological treatment streams. Where such pathways are limited the circular advantage might become upstream waste avoidance and avoided virgin extraction - instead of actual biological cycling.

Overall, the environmental case is best for soybean residue based cat litter if (1) the quantity of residue diversion is large, (2) processing is energy efficient, and (3) end of life pathways have minimum environmental burdens. A defensible sustainability argument needs to therefore combine life cycle logic, carbon and waste accounting and circular design requirements so as not to overstate benefits whilst also making a credible waste to value case (Thomas et al, 2024; Aduba et al, 2025; Faria et al, 2023; Maroušková, 2023).

Diagram 2: Environmental Impact Comparison: Traditional Litter vs. Soybean Residue Litter *(Vasiliauskienė et al., 2023)*

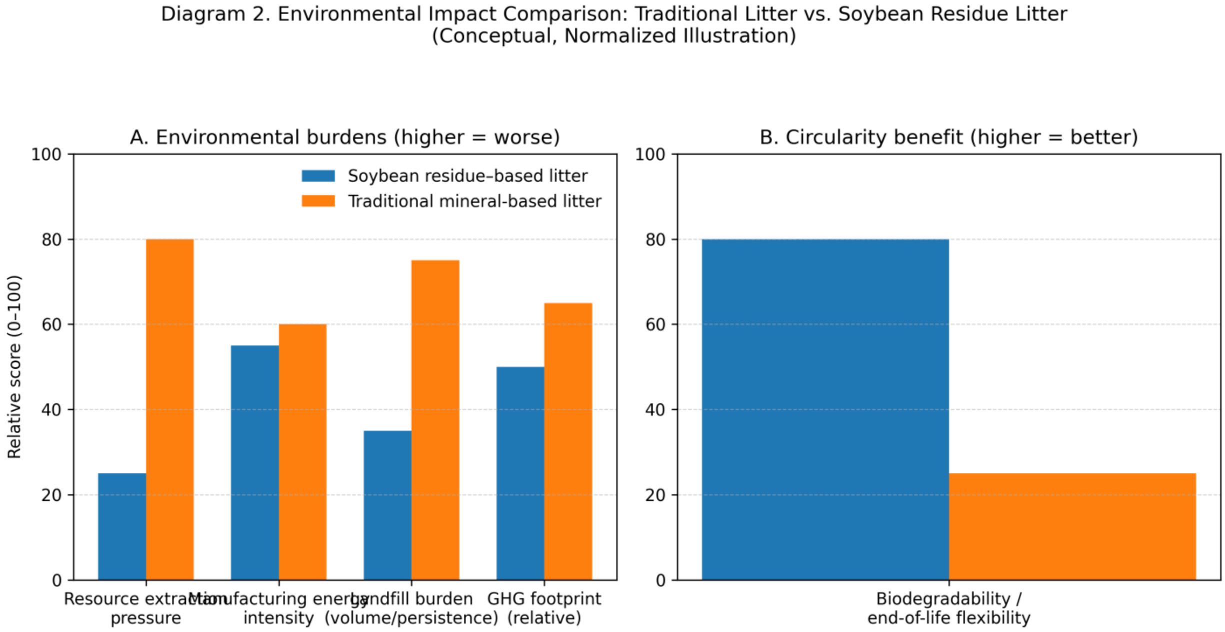
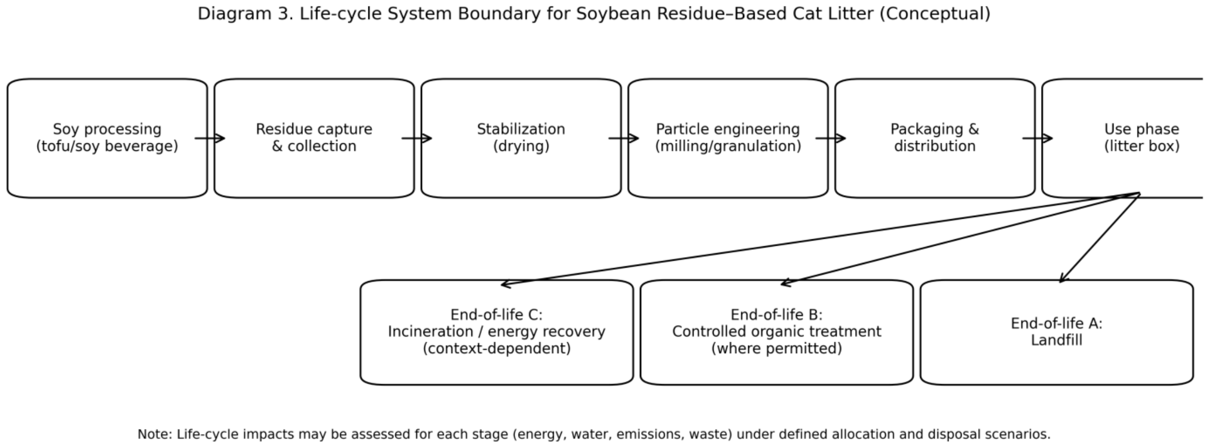


Diagram 3: Life-cycle Analysis of Soybean Residue-Based Cat Litter *(Sirohi et al., 2025)*



6. IMPLICATIONS FOR INDUSTRY AND PRACTICE

The HI soybean residue based CAT litter is just one example of such a concept, but the conversion of a waste-to-value concept into an industry-ready product requires further development aspects such as scalability, integration of the supply chain, and the ability to demonstrate credible economic and sustainability benefits at commercial volumes. While results from the lab or pilot scale can be used to validate the feasibility of the process, in order to be industry adopted there must be consistent sourcing of feedstocks, consistent processing and coupling with existing manufacturing and retail distribution systems. In this context, soybean residue has a structurally attractive input stream as a result of continuous production in tofu and soy beverage plants, making it potentially possible to capture the residue in a stable way with high production volumes provided that the logistics and processing are engineered in the right way (Karim et al., 2025).

6.1, Scales Processing Soybean Residue Scalability

Scaling-up production involves the conversion of a high moisture by-product to a shelf-stable and standardized granular product product at competitive cost. A major limiting factor is that the soybeans are concentrated in locations near food-processing centers and the demand for cat litter is not concentrated in the consumer market. This makes the transportation, drying energy intensity and storage conditions critical determining factors in scaling. For industrial-scale production, it seems likely that locations for processing and/or plant-based protein production would therefore be co-located closer to where the tofu is produced to minimize wet-material transport and associated risk of spoilage. Additionally, scalable systems should be able to handle the variability of feedstock (composition, moisture, fibre fraction) which may impact the durability and absorption (and odour) performance of granules. Therefore, commercial pathways would have to have robust quality control protocols and possibly blending strategies to allow batches to be consistent from batch to batch (Karim et al., 2025).

6.2 Integration With Existing Supply Chains of Pet Care

Integration into pet care supply chains, in terms of compatibility of packaging format, logistics at the point of sale, and consumer expectations of use. Soybean residue litter used for such materials must conform to handling requirements such as stable size of granules, lack of dust release by pouring the residue, and acceptable shelf-life. From the supply chain perspective, integration is easy, if the product can be produced in a standardised product size and can be distributed through conventional channels used for pet hygiene products. Wider sustainability-driven transitions in waste valorisation are emphasised in terms of the importance of ensuring successful adoption often requires the balancing of technical feasibility with market infrastructure - particularly ensuring that product performance and cost of distribution is competitive with established alternatives (Verma et al., 2026). In addition, supply chain integration could reinforce by partnerships among tofu producers, waste management operators, and pet care manufacturers to allow combining the recovery and conversion of residues.

6.3 Benefits of Economic and Sustainability for the Pet Care Industry

The economic case for soybean residue cat litter is related to (i) lower raw material costs (as the feedstock is a by-product), (ii) avoided disposal costs linked to the waste producers and (iii) the possible consumer willingness to use more sustainable products. Sustainability benefits - benefits on the environment burden caused by the extraction of minerals, diversion of landfills and contribution towards circular economy narratives of growing importance for product differentiation in consumer markets. However, these benefits need to be underpinned by operational evidence especially regarding energy efficiency in drying and net emissions profile in the manufacturing and distributing (Marieswaran et al., 2025). If these factors can be optimized, soybean residue litter can offer a credible pathway toward both the improvement of the environment and cost stabilization in lieu of raw material procurement.

6.4 Limitations and Suggestions for Future Research

Despite it is a promising, there are technical and implementation limitations of soybean residue litter. First, high moisture content requires drying and such energy consumption may be high without optimized/integrated waste heat recovery. Second, organic residue systems may be more sensitive to microbial growth, if the controls regarding storage and hygiene are not sufficiently implemented. Third, the handling of end-of-life is complex as used litter is biologically contaminated and may not be fit for composting, in many parts of the world. Future research should therefore focus on (a) energy optimized drying and densification, (b) binders and odour control strategies with low toxicity and high retention of biodegradability, (c) standardized test protocols for litter box performance tested in the long-term and (d) end-of-life feasibility studies for different regions. Related efforts to turn organic and animal wastes into added value products emphasize the need for safety constraints and operational feasibility in the transition from pilot studies to commercial deployment of bio-based waste valorisation strategies applied to produce consumer-facing products (Adetunji et al., 2021).

Table 2. Economic Benefits of Soybean Residue Cat Litter in the Pet Care Industry
(Marieswaran et al., 2025)

Economic lever	Mechanism	Expected benefit category	Industry relevance
Reduced feedstock cost	By-product sourcing vs. virgin mineral input	Lower raw material procurement cost	Improves margin resilience
Avoided disposal cost	Diverts residue from landfill/handling fees	Reduced waste management expenditure	Incentivizes producer partnerships
Value-added revenue stream	Converts low-value residue into sellable product	New product line / diversification	Supports circular business models
Potential logistics optimization	Co-location near tofu processing sites	Lower transport losses/spoilage risk	Improves scalability feasibility
Sustainability-linked market demand	Preference for eco-oriented products	Revenue uplift / brand differentiation	Strengthens competitiveness

7. CONCLUSION

This study examined the feasibility of soybean's residue (tofu by-product) production to produce a sustainable cat litter material in the waste to value concept. Throughout the duration of the evaluation, soybean residue was identified as an underutilized stream of biomass with the functional potential to be utilized as a pet care application especially because of the fibrous nature of soybean residue and its ability to absorb moisture when processed appropriately. The intensity of valorisation pathway has been found to transform food processing residues from disposal burden to usable and better value materials for better environmental results and resource efficiency (Oyedeji et al., 2024).

From a performance point of view the evaluated attributes - absorption behaviour, liquid retention, clumping mechanisms and dust aspects - highlight the fact that it is possible to design soybean residue to cope with some of the functional demands of cat litter if drying, particle engineering and formulation is optimized. While traditional litters made of mineral-based formulation offer high levels of handling stability and predictable performance profiles the testing of residue-based alternatives have shown promising ability in terms of reducing the dependence of the extractive material stream and increasing flexibility of end-of-life treatment where organic treatment routes are feasible. These performance and environmental trade-offs reveal the value of well considered material engineering decisions (e.g granularity design and binder selection) and sustainability criteria instead of being viewed as independent goals to be considered (Oyedeji et al., 2024).

In terms of sustainable material innovation this work belongs to the field of applied materials and sustainability research in demonstrating the concept of biogenic residue as a sustainable resource can be used for the production of the useful consumer product by via focused processing and system evaluation. The research backs the broader premise that by-products from the agricultural and food industry can be used as renewable feedstocks for the engineering of materials, which will help to diversify sustainable materials options that go beyond conventional uses of biopolymers and packaging focused applications. Such innovations have been especially relevant to sectors that fall under the consumption of goods and services like pet care because high-volume consumables create persistent waste streams and as such are meaningful points for sustainability-driven substitution (Bhoi et al., 2024).

Finally, the implications are not only on a particular case of cat litter. The soybean residue pathway illustrates a model that applies to the implementation of the circular economy in consumer products: The capture of an abundant by-product, stabilization of the by-product through efficient processing, engineering of the functionality to consumer expectations and incorporation into scalable value chains. Industry 5.0-based management approaches of waste are even more emphasising the role of system integration, process optimisation and circular design in achieving valorisation of waste at commercial scale (Gaikwad and Anerao, 2025). Overall, results are promising in relation to soy bean residue based cat litter as a feasible waste to value stream to alleviate the pressure from food processing waste streams, whilst allowing a tangible circularity in everyday consumer products.

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