


Closing the Loop: Evaluating Food Waste-to-Feed Pathways for a Circular Food System

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Every year, one-third of all food produced—about 2.5 billion metric tonnes valued at over $1 trillion—is lost or wasted (WWF, 2021; UNFCCC, 2024). Tackling this challenge requires several powerful strategies. The most impactful approach is preventing food waste across the supply chain and at the consumer level; this delivers the greatest financial and environmental gains. Food rescue is the next critical tactic, helping ensure that surplus food continues to fulfill its highest purpose: nourishing people, particularly those most in need.

Yet even with the best systems in place, some food waste is inevitable. That's where recycling solutions step in. Among them, channeling safe food side streams into animal nutrition stands out and is widely used. In the U.S., 11.4% of surplus food was repurposed as animal feed in 2024 (ReFED Insights Engine).

Done effectively, this practice not only diverts waste from landfills and cuts resulting emissions, but also has the potential (under certain conditions)[1] to displace demand for resource-intensive feed crops like soy and corn. It can close nutrient loops, reduce disposal costs for businesses, and increase food security and climate wins.

With feed prices rising (USDA, 2025) and climate scrutiny of business activity intensifying, pathways that transform unused food like waste whey, spent grain, supermarket trimmings, or even post-consumer scraps into feed ingredients are unlocking double value: new revenue streams for food businesses and lower input costs for livestock producers.

Some approaches, like using spent brewery grains for cattle or bakery items for poultry and pigs, are long-established, widely scaled, and valuable in the right contexts. But their growth potential and the types of food waste inputs they can recycle can be limited. Meanwhile, emerging solutions are opening new frontiers for businesses and creating opportunities for funders to explore.

This report reviews eight waste-to-feed technologies and dives deep into four innovative and underutilized approaches: swill, single-cell proteins, insect farming, and biochar feed additives. By examining production processes, commercial viability (including regulatory statuses and business economics), environmental footprints, and case studies, we identify which pathways are gaining real commercial traction and which present the greatest opportunities for positive impact.

> **For capital providers and food businesses alike, this report offers insights to a roadmap to the most fundable—and genuinely circular—solutions in waste-to-feed.**

ReFED would like to thank The Centre for Feed Innovation for their contribution to the research and analysis in this report.

[1] Additional research is required to confirm overall climate benefits of utilizing food waste for animal feed. Due to the potential for waste-to-feed pathways to reduce the cost of feed, rebound effects—where lower feed costs lead to livestock expansion—may diminish or even negate overall benefits as discussed in the article *"Rebound effects may undermine the benefits of upcycling food waste and food processing by-products as animal feed in China"* (Long et al., 2025).

Summary of Food Waste Pathways to Animal Feed

To help compare pathways, we use Technological Readiness Levels (TRLs) estimated by The Centre for Feed Innovation. TRL scores range from 1–2 (concept) and 3–4 (lab) to 5 (pilot), 6 (demo), 7 (first-of-a-kind commercial), 8 (early commercial), and 9 (bankable multi-plant).

ESTABLISHED ↑ ↓ EXPERIMENTAL

Former-Food (Bakery) Meal

Typical Inputs: Pre-consumer bread, biscuits, cereals (de-packaged, dried)

Products & Markets: Energy-dense "biscuit meal" for poultry and pigs

Environmental Benefit: *Medium* - Strong diversion from waste; energy impact depends on drying needs

Major Tailwinds: Very low feedstock cost; familiar formulation

Major Headwinds: High-energy needs for drying; variable input supply; competition with anaerobic digestion

Technological Readiness Level: 9

Estimated Annual Global Commercial Scale (MT Of Production/Year): > 10 million[2]

Growth Outlook: *Mature market with limited growth potential* - Expansion constrained by available bakery waste volumes

Brewers' Spent Grain (BSG)

Typical Inputs: Wet spent grains

Products & Markets: Wet distiller's or brewer's grain for cattle; distillers dried grains with solubles, DDGS for non-ruminants

Environmental Benefit: *High* - High if fed wet and local; moderate when dried for export due to energy use and transport

Major Tailwinds: Brewer–farmer mutual benefits; strong nutrient mix

Major Headwinds: Wet grain spoils quickly; costly drying for export

Technological Readiness Level: 9

Estimated Annual Global Commercial Scale (MT Of Production/Year): >25 million[3]

Growth Outlook: *Mature market with limited growth potential* - Expansion constrained by available BSG; more room for upgrading BSG into premium feed ingredients than for increasing total tonnage

Protein Hydrolysates

Typical Inputs: Fish or poultry byproducts (conventional); grain and pulses byproducts (novel)

Products & Markets: Peptide-rich concentrates for aqua and pets

Environmental Benefit: *Medium* - Utilizes byproducts; impacts hinge on processing energy & effluent control

Major Tailwinds: High palatability; functional peptides

Major Headwinds: Finite input pool; odour/spec controls

Technological Readiness Level: 9 (conventional); 7-8 (novel)

Estimated Annual Global Commercial Scale (MT Of Production/Year): ≈ 250 thousand[4]

Growth Outlook: *Moderate growth* - Supply bound by production cost and byproducts availability

Swill

Typical Inputs: Post-consumer mixed food waste (vegetal, animal, or combined), sourced from retail, food-service, and households

Products & Markets: Heat-treated wet pig feed

Environmental Benefit: *High* - Can cut net GHG and divert waste, but depends on strict heat-treatment and traceability

Major Tailwinds: Revenue from tipping fees; direct food waste utilisation; pig producers gain low-cost feed

Major Headwinds: Prohibited in the EU; permitted for pigs only in the US at the federal level, but banned in 25 states; biosecurity concerns; depackaging/transport costs

Technological Readiness Level: 7–9

Estimated Annual Global Commercial Scale (MT Of Production/Year): > 1 million

Growth Outlook: *Regulation and infrastructure-limited* - Use and legality vary widely; niche growth for swill via corporate partnerships under strict traceability and heat-treatment rules

Single-Cell Proteins (SCP)

Typical Inputs: Whey, BSG hydrolysate, methanol, off-gases, molasses

Products & Markets: Bacterial, yeast, or microalgae meals for aqua, poultry, and pets

Environmental Benefit: *Medium* - Very low land/water use; energy use can drive environmental footprint

Major Tailwinds: Consistent quality; rapid scaling; land- and water-light; microalgae variants can create functional nutrients (DHA/EPA)

Major Headwinds: High CapEx; drying energy requirements; regulatory approvals

Technological Readiness Level: 7–8

Estimated Annual Global Commercial Scale (MT Of Production/Year): ≈ 50 thousand[5]

Growth Outlook: *Scaling industry with moderate growth potential* - First-of-a-kind facilities expanding, though high CapEx needs; requires energy and feedstock integration

Insect Farming

Typical Inputs: Former foods and food processing byproducts (e.g., BSGs, fruit and vegetable trimmings), commercial animal feeds

Products & Markets: Insect meal or oil for aqua, pets, pigs, and poultry

Environmental Benefit: *Low* - Circularity benefits & emissions reductions limited by feedstock regulations; energy-intensive production

Major Tailwinds: High historical investment; protein-rich product

Major Headwinds: High cost from feedstock and for drying; poor adoption in target markets; regulation prohibits use of most post-consumer food waste as feedstock

Technological Readiness Level: 7

Estimated Annual Global Commercial Scale (MT Of Production/Year): ≈ 30 thousand[5]

Growth Outlook: *Regulation-limited, low growth* - Can't cheaply or efficiently use currently legal waste streams; does not provide a circular solution; high CapEx requirements

Silage

Typical Inputs: Wet surplus foods (fruit, vegetal, bakery returns, BSG); sometimes blended with dry materials

Products & Markets: Fermented fodder for cattle and other ruminants

Environmental Benefit: *High* - Fermentation is low-energy; benefits depend on short-haul logistics and clean inputs

Major Tailwinds: Low processing cost; decentralized/local adoption; reduces methane from unmanaged waste

Major Headwinds: Feedstock variability; nutrient imbalances; short shelf-life if not well managed

Technological Readiness Level: 5-7

Estimated Annual Global Commercial Scale (MT Of Production/Year): > 500 thousand

Growth Outlook: *Emerging potential* - Could scale through decentralized, farm-linked models where wet food waste is available locally

Biochar Feed Additive

Typical Inputs: Feed-grade pyrolysed biomass

Products & Markets: Functional additive for ruminants, poultry, and pigs

Environmental Benefit: *High* - High potential for carbon storage

Major Tailwinds: Potential methane and ammonia reduction; potential carbon credit upside

Major Headwinds: Mixed and limited trial data; regulatory gap

Technological Readiness Level: 5–6

Estimated Annual Global Commercial Scale (MT Of Production/Year): 80 thousand[6]

Growth Outlook: *Emerging niche with moderate potential* - Early-stage adoption; potential boost from carbon-credit markets and methane-reduction policies, but requires further validation of animal-performance benefits

ESTABLISHED

EXPERIMENTAL

[2] Estimated ~20% of total global bakery waste
[3] ~71% of the ~37 million MT of brewers' spent grains produced annually is used in animal feed (Grandview research, 2022; Outeriño et al., 2024)
[4] Limited publicly available data, estimate based on industry conversations
[5] Production utilising both waste & non-waste feedstocks. Specific production volumes utilising waste only are unknown
[6] ~25% of global production

Supply Chain Diagram

Mapping of how key food-industry byproducts can flow into waste-to-feed pathways, guiding company strategy and investor insight.

PRODUCTION	Agriculture, forestry, bioenergy	Biomass residues (husks, nutshells, crop residues)
	Farming	Fruit & vegetable surplus (off-spec)
PROCESSING	Brewing, distilling	Wet spent grain (breweries, distilleries)
	Dairy	Whey, dairy residues
	Meat & seafood	Fish trimmings, poultry byproducts, slaughterhouse waste
	Food manufacturing	Fruit & vegetable surplus (trimming)
		Bread, biscuits, cereals (surplus, off-spec)
	Milling, oilseed, ethanol	Grain & pulse byproducts (bran, hulls, press cakes, DDGS)
	Industrial fermentation	Off-gases (CO_2, CO_1, H_2), methanol, ethanol, syngas
DISTRUBUTION AND END MARKETS	Retail & food service	Bread, biscuits, cereals (surplus, returns, off-spec)
		Fruit & vegetable surplus (trimming, unsold)
		Mixed post-consumer food waste
	Households	Mixed post-consumer food waste

KEY

- Former-Food (Bakery) Meal
- Brewers' Spent Grain (BSG)
- Protein Hydrolysates
- Swill
- Single-Cell Proteins (SCP)
- Insect Farming
- Silage
- Biochar Feed Additive

Deep Dive: Swill

Post-consumer waste from retail, food service, and households has the potential to displace large volumes of conventional feed, but current capacity is limited by safety and regulation. Swill—heat-treated post-consumer scraps—is proven at scale in Asia but banned in most Western markets over disease concerns. It represents a powerful pathway to reintroducing food waste into feed systems.

Pathway Overview

Inputs & Processing

Swill draws on post-consumer streams such as plate scrapings, cooked foods, and mixed retail discards, often including meat and dairy. These inputs are depackaged, separated by source, and heat-treated to neutralize pathogens and ensure safety (USDA APHIS, 2019).

Products

Swill processing produces a wet, heat-treated mash fed directly to pigs. It can also occasionally be dried into a meal.

Target Markets

Swill is mainly used in pig diets, reflecting pigs' tolerance for varied inputs (Shurson et al., 2023).

Commercial Viability

Status & Scale

Swill feeding is commercially proven and mainstream in East Asia, particularly Japan and South Korea, where regulated systems enable large-scale diversion of post-consumer food waste into pig feed. For example, Japan's eco-feed program produces over 1 million MT annually (Nakaishi and Takayabu, 2022), and South Korea operates large municipal plants (Lee et al., 2024).[7] However, China's Ministry of Agriculture and Rural Affairs banned untreated swill feeding to pigs following the African Swine fever outbreak (DEFRA, 2018), swill remains banned across the EU (EC, 2003/328/EC), faces tight federal regulation in the U.S. under the Swine Health Protection Act due to disease concerns, and is banned in many U.S. states.

Region	Regulatory Status	Commercial Status
EU & UK	Strict ban on catering waste since 2001 Foot & Mouth Disease outbreak	No commercial activity
U.S.	Highly regulated: swill must be heat-treated at 100°C/30 min; banned in 25 states (APHIS, 2024)	R&D/Pilot production only
Japan & South Korea	Permitted with mandatory treatment and collection systems	Mature, industrial-scale production
China	Untreated swill feeding banned since 2019	No commercial activity; former large swill market shut down
Rest of World	Generally prohibited or highly restricted	Minimal activity beyond pilots

Economics & Operating Costs

The economics of swill are defined by operating conditions and local context. Reported production costs are scarce, but case studies show that viability depends on short transport distances, reliable collection systems, and the ability to capture waste disposal charges (tipping fees). For example, due to centralized food waste recycling systems in Asia, swill comes in at 40–60% of the cost of conventional animal feeds in the region (zu Ermgassen et al., 2016).

Operating cost drivers include:

- **Energy intensity:** Cooking at 70–100°C is required to ensure food safety, making thermal processing a major cost (World Biogas Association, 2018; USDA APHIS, 2019).
- **Cost offsets:** In some countries, tipping fees or waste disposal charges partly offset operating costs, as seen in South Korea (Lee et al., 2024).
- **Depackaging:** Collection, sorting, and depackaging of mixed post-consumer food waste add complexity and cost, requiring coordinated municipal systems.
- **Location:** Swill inputs and outputs are heavy and perishable, making proximity to waste sources and farms a critical determinant of economic viability.

Capital Expenditure (CapEx)

Swill systems require modest up-front capital investment compared to more infrastructure intensive food waste-to-feed pathways. The main required assets are cooking, sterilization, and depackaging equipment, which are often adapted from existing waste-management or feed-processing facilities.

Headwinds & Risks

- **Regulatory barriers:** Heavily constrained by biosecurity rules in Western markets and China due to zoonotic disease risk.
- **Logistics dependence:** Requires short, reliable logistics chains to remain cost-effective, which may limit scalability.
- **Market limitations:** Use is restricted largely to pigs, due to their tolerance for varied dietary inputs.

Tailwinds & Opportunities

- **Food waste diversion at scale:** Demonstrates that post-consumer food waste can be safely and effectively diverted into feed when oversight and collection systems are in place.
- **Dual revenue potential:** Can generate dual income streams via disposal fees from waste generators and low-cost pig feed at scale.

[7] In 2019, feeding leftover food to pigs was banned in South Korea following an outbreak of African Swine Fever. In 2024, feeding leftover food to pigs has slowly resumed under strict quarantine management (Lee, 2024).

Environmental Impact

Swill could create environmental gains by diverting meaningful volumes of food waste from landfill and potentially displacing land- and emissions-intensive crops as a feed ingredient. Life cycle assessments (LCAs) suggest that swill can deliver net-negative emissions when methane avoidance and avoided feed production are included (zu Ermgassen et al., 2016). However, caution is required as rebound effects—where lower feed costs lead to livestock expansion—may meaningfully diminish overall climate benefits for swill given its potential for much lower cost as compared to conventional animal feeds (Long et al., 2025).

System Dependencies

The net impact depends on processing energy sources and logistics. Integrating renewable heat or biogas maximizes climate benefits.

Impact Area	Findings
Climate Change	Avoids methane emissions from landfilled food waste and displaces traditional soy and corn feed. LCAs show potential for net-negative carbon balances, though benefits can be eroded with the use of fossil-fuel energy for heating treatment.
Land & Water	Requires meaningfully less land than traditional feed for pigs. For example, widespread use of swill could cut EU pork production land use by 21.5% if re-legalized in the region (zu Ermgassen et al., 2016).
Nutrient Cycling	Returns food nutrients to animals rather than losing them to landfill. Requires careful management of salt and contaminants.

Case Studies

Eco-Feed Program | *Japan*

Japan's Ministry of Agriculture, Forestry and Fisheries oversees a nationwide program where food waste is collected, depackaged, and heat-treated into pig feed. In 2019, the program's output exceeded 1.19 million MT of total digestible nutrient (TDN), amounting to ~ 6% of total concentrate feed (Nakaishi & Takayabu, 2022). The program shows how strict regulation and government oversight can safely scale swill feeding into a mainstream, industrial pathway.

Municipal food waste-to-feed facilities | *South Korea*

Seoul's Dobong facility processes 70–80 MT of food waste per day into ~8–9 MT of sanitized swill feed, integrated into a broader municipal recycling system (Korea Times, 2020; Lee et al., 2024). Nearly 300 such facilities nationwide are supported by landfill bans and a pay-as-you-throw system. This model demonstrates how embedding swill production within municipal infrastructure can deliver both waste management and feed substitution at scale.

Las Vegas Livestock | *United States*

Las Vegas Livestock collects casino and retail scraps from the Las Vegas Strip, heat-treats them under USDA rules, and feeds the output to pigs on-site. This example shows that swill can operate successfully even in restrictive environments, though scaling remains limited by local regulation and consumer perception.

Outlook

Swill production in Asia demonstrates an industrial-scale viable use of post-consumer food waste. Unlocking swill's full potential requires risk-based regulatory reform in Europe and the U.S. (including across states), investment in collection and processing infrastructure, and systems to guarantee consistent quality and biosecurity.

Deep Dive: Single-Cell Proteins (SCP) from Food-Industry Side Streams

Single-cell proteins (SCP) are microbial proteins produced by growing yeasts, fungi, or microalgae fed with pre-consumer food-industry side streams. This fermentation process concentrates protein, improves digestibility, and can generate added nutrients like omega-3 fatty acids, creating high-value feed ingredients. SCPs offer a promising circular solution to reduce reliance on fishmeal and soy in aquafeed and livestock feed, though regulatory limits on what can be used as feedstock and high production costs remain barriers to scale.

Pathway Overview

Inputs & Processing

SCP are produced from clean, pre-consumer side streams of food manufacturing, such as whey from dairies, brewery wastewaters, potato residues, and molasses (Sekoai et al., 2024; Outeiriño et al., 2024). These streams are generated in large, steady volumes but often have low-value uses like energy generation, making them attractive feedstocks for fermenting into protein.

These waste-based inputs are used as a carbon and nutrient source to cultivate microorganisms such as yeast, bacteria, microalgae, or fungi in bioreactors under controlled conditions via a fermentation process. After sufficient growth, the microbial cells are harvested, dried, and processed into a protein-rich meal, or functional nutrients such as omega-3 fatty acids are extracted from the biomass (Reihani and Khosravi-Dharani, 2019).

Products

This fermentation process creates high-protein meals and oils. The resulting products typically contain 60-70% of highly digestible protein (Brasotin et al., 2021) and, in some cases, long-chain omega-3 fatty acids such as EPA and DHA (Ma and Hu, 2023), creating a premium feed ingredient.

Target Markets

The strongest markets for these products are aquafeed and pet food, where digestibility and omega-3 content are highly valued. Use in poultry and swine is emerging as more performance data becomes available and regulatory approvals come through (Bianco et al., 2020; Ng et al., 2024).

Commercial Viability

Status & Scale

SCP production from food-industry side streams has entered early commercial deployment. The dominant model is the use of modular, co-located first-of-a-kind (FOAK) plants that produce a few thousand metric tonnes of feed per year. They are designed for replication and co-location across dairies, breweries, and distilleries, rather than as mega-facilities. Global production capacity is still limited, but the replication model has been increasingly validated. Furthermore, SCP production from non-food industry side streams have demonstrated successful scaled production in Asia, with plants like Calysta's in China that have the capacity to produce 20K MT of protein per year (Calysta).

Price to producers in aquafeed and aquaculture is estimated to be ~$1,200-$2,500 per MT (Jean & Brown, 2024; Hatch Innovation Services), positioning SCP suppliers competitively between fishmeal and soybean meal.

Region	Regulatory Status	Commercial Status
EU & UK	EFSA approval required; pre-consumer byproducts permitted, post-consumer food waste prohibited	Early commercial, first-of-a-kind units, often co-located with breweries/dairies
U.S.	FDA evaluates SCP case-by-case under GRAS or food additive petitions, only approved food-grade substrates (e.g. starch or ethanol co-products); no use of post-consumer food waste	Early commercial in aquafeed and pet food, most production still at pilot/ demonstration scale
China	Product-specific regulatory approvals	Demonstration to early commercial using methane-based gas fermentation, mainly in aquafeed
Japan & South Korea	Product-specific regulatory approvals; slower than China	Pilot to early commercial activity
Rest of World	Limited approvals, case-by-case	Mostly R&D and pilots

Economics & Operating Costs

Estimated production costs for SCPs range using food waste from ~$1,500 - $6,960 USD/MT protein depending upon the feedstock used, with the majority of estimates at the middle and higher end of this range (Li et al., 2025; Moscariello et al., 2025; Matassa et al., 2022).

Costs vary by organism, feedstock, and business model, but several key operating cost drivers are consistent:

- **Feedstock reliability & proximity:** Access to steady, local inputs (e.g., from dairies, breweries, distilleries) lowers input risk, cut transport costs for heavy wet streams, and reduce pretreatment needs.
- **Post-fermentation drying:** The single largest utility load, often more than half of total energy use.
- **Pre-concentration & heat integration:** Using centrifugation or filtration for dewatering cheaply instead of evaporation or sedimentation and tapping into waste steam or low-cost heat from host sites can lower both operating costs and carbon intensity.
- **Fermentation process:** While this is less costly than drying, it requires tight process control to sustain high titers (target protein or oil concentration) and prevent contamination, which together enable cost-effective production.

Capital Expenditure (CapEx)

Commercial-scale SCP production is capital intensive, though costs vary widely depending on the platform, feedstock, and scale. Recent data from food waste valorization pathways provide a useful benchmark. Enifer, for example, announced an investment of €33 million (~USD 35 million) for a facility designed to produce 3,000 MT/year of fungal SCP from food industry side streams (Enifer, 2024). On a capacity basis, this equates to roughly $11,700 per annual MT of capacity.

This ratio is broadly comparable to smaller-scale gas fermentation plants but at a much lower absolute investment, reflecting the simpler engineering footprint of biomass-fed systems. Whereas gas fermentation requires specialized reactors, compression, and extensive safety systems, food waste valorization typically entails lower CapEx tied primarily to feedstock pretreatment, handling, and storage infrastructure.

As with other biomanufacturing processes, economies of scale are likely to reduce unit CapEx at higher capacities. However, the reliance on heterogeneous and seasonally variable side streams may limit scale-up compared to more uniform gas or sugar inputs, anchoring most near-term projects in the low- to mid-thousand MT range.

Headwinds & Risks

- **Energy dependence:** Margins are highly sensitive to drying and utility costs; without access to waste heat or low-cost steam, both economics and life cycle impacts deteriorate.
- **Feedstock competition:** Key side-streams such as whey already serve high-value markets, limiting low-cost input availability.
- **Regulatory hurdles:** Organism and product-specific approvals can slow market entry and add compliance costs.
- **Market adoption:** Uptake is gradual, requiring trust, validation, and performance data across target livestock species.

Tailwinds & Opportunities

- **High demand and premium pricing:** Functional nutrient enrichment (i.e., EPA/DHA enrichment and high digestibility) drives strong demand and enables price premiums in aquafeed and pet food.
- **Consistency advantage:** Year-round, stable supply offers benefits over volatile marine and crop proteins for traditional fishmeal and soy-based feed.
- **Co-location synergies:** Host sites gain by-product monetization, lower disposal costs, and improved ESG profiles, while producers secure reliable feedstock and low-cost utilities.

Environmental Impact

The environmental potential of SCPs comes from the ability to utilize waste from food production to produce a feed ingredient with a lower environmental footprint than traditional feed ingredients. When co-located with food plants and powered by renewable or waste energy, SCPs can consistently deliver lower impacts than soy and fishmeal. LCAs highlight several advantages: reduced greenhouse gas emissions, negligible land and water use, and nutrient recovery from industrial side streams (Sillman et al., 2020; Wada et al., 2022). However, when relying upon fossil-based energy sources or non-waste derived feedstocks, the environmental benefits are less pronounced.

System Dependencies

Environmental outcomes depend upon the type of feedstock and the energy source for fermentation and drying. Using industrial effluents yields the strongest footprint reduction, however reliance on fossil energy can diminish benefits. Transporting bulky, water-rich inputs long distances also raises impacts, reinforcing the importance of co-location.

Impact Area	Findings
Climate Change	LCAs show that SCP using crude pea starch has approx. 1.2 times lower emissions than best-case soybean meal, and approx. 6.8 times lower emissions than the average soybean meal. Compared to fishmeal, crude pea starch SCP has approx. 4.1–8.0 times lower emissions than directed pelagic fishmeal (Aidoo et al., 2024). SCPs using agricultural waste waters as feedstocks can also generate reductions in environmental impact; however, use of fossil fuel-based energy for drying can erode these gains (Wada et al., 2022).
Land & Water	Requires no cropland and negligible irrigation, avoiding deforestation and biodiversity loss associated with soy expansion (Sillman et al., 2020).
Nutrient Cycling	Fermentation captures nitrogen and phosphorus from side streams (e.g., dairy permeate, potato wastewater), reducing eutrophication risks and retaining nutrients in the food chain.

Case Studies

Enifer: FOAK mycoprotein from food-industry side streams | *Finland*

Enifer is commissioning a ~3K MT per year PEKILO® mycoprotein plant in Kirkkonummi, Finland, as a brownfield project on the site of a former sugar factory. The €33 million project integrates food side-stream inputs with existing utilities, wastewater treatment, and steam (Enifer, 2024; Sweco, 2024). The case demonstrates that modular, co-located SCP can secure commercial financing and provide a replicable template for production near major food-industry clusters.

MiAlgae: DHA-rich microalgae on distillery residues | *United Kingdom*

MiAlgae cultures microalgae on whisky-distillery co-products, producing DHA-rich biomass for aquafeed and pet food. After validating operations at a demonstrator site, the company raised £14 million in 2024 to build an industrial-scale plant in Scotland's Central Belt (MiAlgae, 2024). Located near multiple distilleries, the facility will scale to ~3K MT per year of omega-3 fatty acid capacity (Fishfarmingexpert, 2024). MiAlgae has long-term partnerships with both distilleries and feed producers, securing both feedstock sources and customers. This case highlights how SCP can substitute marine oils in premium markets through modular, co-located growth.

Outlook

SCP is a small but commercially promising segment with strong tailwinds in feed security, sustainability, and circularity, and a clear path to replication. Modular FOAK plants are proving to be bankable and creating a clear template for replication at dairies, breweries, and distilleries. SCP's ability to scale further rests on three conditions: co-location with input streams, efficient drying to control costs, and access to premium offtake markets. Meeting these conditions allows SCP to reach competitive economics and operate as a commercially viable ingredient.

Deep Dive: Insect Meal

Industrial insect farming feeds black soldier fly (BSF) larvae, yellow mealworm larvae, and crickets on organic substrates to generate insect meal, oil, and frass (insect waste). Initially, insects were positioned as a potential food waste solution, using waste streams to produce a high-protein product. However, due to regulation in key jurisdictions and nutritional needs for insect growth, insects can only be reared on feed- or food-grade materials already used in conventional livestock feeds, resulting in a challenge to the circularity potential of using insects. Regulatory restrictions, high costs, and slow commercial progress to date have further constrained their potential as a highly viable animal feed ingredient, leaving insect meal presently as a more complicated food waste pathway than once anticipated.

Pathway Overview

Inputs & Processing

In most major jurisdictions, including the United States, United Kingdom, and European Union, insect production for feed is restricted to feed-grade or food-grade substrates, due to food safety and biosecurity concerns. This means that post-consumer catering waste, household scraps, and manure are not permitted as rearing inputs, even though they represent abundant organic side streams. Instead, producers rely on pre-consumer materials such as fruit and vegetable trimmings, cereal-based former foods, and certain food-industry byproducts that are already authorized in conventional livestock feeds.

Insects such as BSF or yellow mealworm larvae are reared on prepared organic substrates under controlled conditions until harvest. The larvae are then killed, dried, and milled to produce a high-protein meal. The lipid fraction is extracted to produce insect oil. Growth cycles and conditions vary depending upon species.

Products

Insects convert inputs into insect meal, oil, and frass. The primary output, insect meal—which can be incorporated into animal feed formulations—typically contains ~55–65% protein and ~10–25% lipid on a dry-matter basis, though composition varies with diet, species, and processing (Glencross et al., 2024).

Target Markets

The target markets for insect meal are aquafeed and pet food, where functionality and branding can support premium pricing, although adoption has been limited so far due to higher cost, lower availability, and consumer acceptance challenges. Insect meals are also permitted for use in poultry and pig feed in the U.S. and EU, but remain more limited in uptake due to the price sensitivity of those markets.

Commercial Viability

Status & Scale

After more than a decade of development, insect farming remains small relative to initial expectations. Global insect meal output is estimated at approximately 30K MT per year (Hatch Innovation Services, 2024), well below projections of 500K MT per year by 2030 (Rabobank, 2021) despite nearly $2 billion invested in the industry over the last decade.

Market prices of €3,500–5,500 (approximately USD 4,100-6,500) per metric tonne have been a key factor in keeping the products in more niche, premium channels. Some major aquafeed producers have trialled inclusion of insect meal in feed formulations, but they report low inclusion rates in recent years (~0.01%) and cite less competitive prices and low production volumes as headwinds to adoption (FAIRR, 2025; Skretting, 2024).

Region	Regulatory Status	Commercial Status
EU & UK	Pre-consumer feed-grade substrates permitted; post-consumer waste prohibited	Pilot and early commercial scale in pet food and aquafeed
U.S.	Permitted on approved feed-grade substrates, subject to FDA/AAFCO; catering waste excluded	Pilot and demonstration in poultry and niche pet food markets
Asia (China, SE Asia)	Generally permitted, but with varying national rules	Demonstration and early commercial (China scaling rapidly); SE Asia hosts smaller operators
Rest of World	Limited approvals, case by case	R&D to pilot activity

Economics & Operating Costs

Estimated production costs for BSF larvae are $3,000–5,500 per metric tonne of dried larvae and $4,000–6,000 per metric tonne of insect protein (Hatch Innovation Services; Rabobank, 2021; Shah and St Jules, 2024; Leipertz et al., 2024).

Costs vary by species, region, and business model, but several key operating cost drivers are consistent:

- **Substrate sourcing:** Regulations prohibit the use of mixed post-consumer food waste, so producers must rely on cleaner byproducts (e.g. grains, ag side streams) that are already in demand for livestock feed, creating competition and higher input costs; feedstocks can account for up to 50% of operating costs.
- **Climate control:** Rearing insects requires stable conditions of ~27–30 °C with regulated airflow and humidity; heating, ventilation, and air conditioning (HVAC) systems are among the most energy-intensive parts of the operation.
- **Drying and processing:** Converting larvae into a safe, storable meal requires energy-heavy drying, adding another major cost layer.
- **Labor intensity:** Insect farming involves frequent handling of eggs, larvae, and trays, plus harvesting and processing; limited automation means labor remains a significant share of operating expenses.

Capital Expenditure (CapEx)

Industrial insect production requires $2,700–19,000 per metric tonne of dried insects per year in capital investment (Shah and St Jules, 2024).

Facilities of 10K MT annual capacity have required $33–45 million of CapEx, while a 100K MT plant has required an $372 million investment (Hatch Innovation Services).

Economies of scale and technological advances may reduce CapEx, but current CapEX requirements can make expansion difficult and potentially limit competitiveness with conventional feed proteins.

Headwinds & Risks

- **Substrate limitations:** The substrates with the highest circularity potential (e.g. post-consumer waste, mixed retail returns) are prohibited by regulation; permitted substrates often show variable nutrition and microbial loads, reducing yields and requiring costly treatment (Sogari et al., 2023; Spykman et al., 2021).
- **High operating costs:** Energy demand for climate control and drying, combined with labor intensity, keeps production costs meaningfully above commodity protein levels.
- **Biosecurity risks:** Disease management and hygiene protocols add further cost and complexity, as well as risks; escapes of BSF have been documented in Europe (Generalovic et al., 2023) and most farms have been found to carry pathogens, including zoonotic species (diseases that can be transmitted from animals to humans) (Gałęcki et al., 2019).
- **Capital intensity:** Large upfront investment requirements mean scale-up depends largely on securing long-term contracts or partnerships to unlock CapEx, which are difficult to obtain. Investment in insect farming declined by 65% between 2022 and 2024 (CFI, 2025), meaningfully adding to this difficulty.
- **Market positioning challenge:** Current focus on pet food and premium aquafeed niches provides some pricing power, but more limited circularity and higher-than-previously-expected environmental impacts present challenges to sustainability-based differentiation and the potential to access other markets.

Tailwinds & Opportunities

- **Cost-reduction potential:** Advances in automation and co-location with agro-industrial sites could significantly lower labor and energy costs over time.
- **Premium market niches:** Pet food and specialised aquafeeds offer profitable outlets, where sustainability branding and functional benefits can support premium pricing.

Environmental Impact

The environmental potential of insect meal depends upon its ability to provide a feed ingredient for aquaculture and livestock with lower environmental impacts than fishmeal or soybean meal, while diverting food waste from landfill. However, without regulatory change to allow the use of post-consumer waste as feedstocks and major reductions in energy intensity in insect production, insect meal will likely be challenged when competing environmentally with soy or fishmeal. LCAs consistently show that insect meal using food waste has much higher footprints than utilizing traditional feed ingredients (Dawson and Salmon, 2024; Roffeis et al., 2020; Smetana et al., 2019; Thévenot et al., 2018).

System Dependencies

Alternative substrates such as post-consumer food waste or chicken manure can reduce emissions by avoiding the burdens of crop production, but these options remain prohibited in most jurisdictions due to food safety regulation. Switching to renewable energy offers further reductions across environmental impacts, though the effect is minor compared with feedstock choice.

Even under best-case conditions—using waste-based feedstocks and 100% renewable energy—insect meal still has approximately 1.5 times higher emissions than fishmeal and approximately four times higher emissions than soybean meal (Dawson and Salmon, 2024).

Impact Area	Findings
Climate Change	Insect meal production using approved, feed-grade feedstocks has approx. four times higher emissions than fishmeal and approx. 13.5 times higher emissions than soybean meal; while using waste-based feedstocks reduces the emissions, this is still approx. 1.8 times higher than fishmeal and approx. 5.5 times higher than soybean meal (Dawson and Salmon, 2024).
Land & Water	Permitted substrates are mostly pre-consumer byproducts already used in livestock feed, offering little land-sparing benefit; insects cannot easily capture otherwise wasted nutrients.
Nutrient Cycling	Frass can be used as a fertilizer, providing a benefit to this byproduct of insect meal production; there are risks of nutrient leaching and over-application if poorly managed.
Ecological & Biosecurity	Escapes of BSF have been documented in Europe, with evidence of hybridization with wild populations (Generalovic et al., 2023); Surveys found 80% of farms carried pathogens, including zoonotic species (diseases that can be transmitted from animals to humans) (Gałęcki et al., 2019).

Case Studies

InnovaFeed & ADM: Co-location with corn processing | *United States*

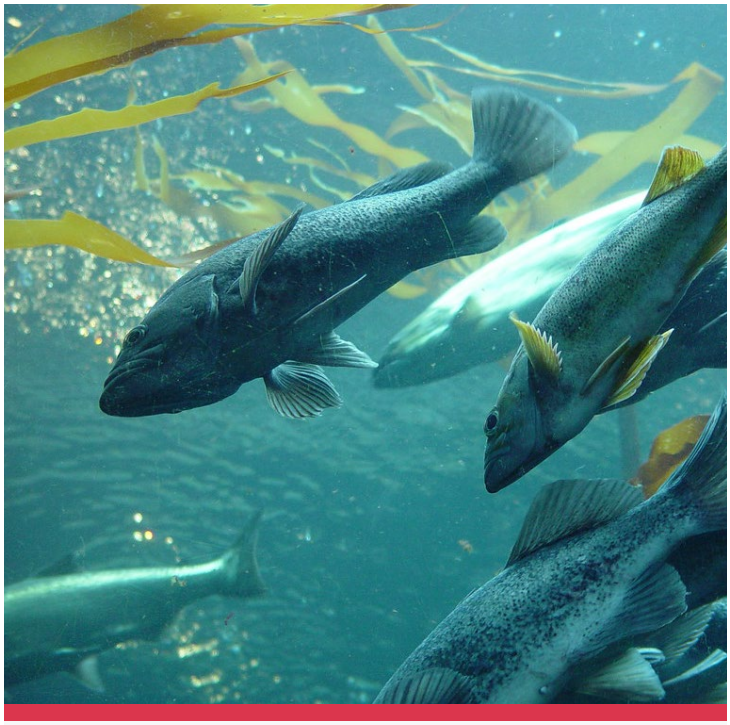
InnovaFeed partnered with Archer Daniels Midland (ADM) to build an insect protein facility in Decatur, Illinois, integrated with ADM's corn wet milling site. The model aimed to use byproducts as inputs, tap ADM's utilities, and plug directly into feed supply chains (ADM, 2022). Whilst InnovaFeed have been reported to have paused operations in August 2025, (Undercurrent News, 2025) they maintain a goal to expand to 10K metric tonnes of protein production per year. The case shows both the strategic potential of co-location with incumbents, and the potential challenges of achieving scale.

Ÿnsect: High-profile scale-up failure | *France*

Ÿnsect raised approximately $600 million (Shah, 2024)—nearly one-third of all global insect-farming investment—to scale highly automated mealworm facilities. Expansion faltered due to construction delays, high energy costs, reliance on expensive inputs, and weak market uptake in aquafeed. Unable to raise further capital, Ÿnsect entered insolvency in February 2025 (Sifted, 2025). This case illustrates how high capital intensity, automation risks, and price-sensitive markets can derail scale-up, even for sector leaders.

AgriProtein: Early pioneer unable to reach scale | *South Africa*

AgriProtein, once a leading BSF pioneer, raised approximately $120 million (Shah, 2024) but failed to scale pilots into cost-competitive production. Regulatory limits blocked access to low-cost food waste substrates, while drying, climate control, and breeding inefficiencies inflated costs. With slow uptake beyond premium niches, the company entered administration in 2021 (Insights Administrationalist, 2021). The case highlights structural cost and regulatory barriers that have consistently constrained insect-farming economics to date.



Outlook

As a food waste pathway, the insect meal sector faces a challenging near-term outlook. Production remains largely constrained to feed-grade substrates and premium niche markets, limiting its current role in large-scale food waste diversion. Higher operating costs, biosecurity risks, and slower adoption in price-sensitive feed markets have continued to weigh on scale-up, and well-publicized failures raise concerns about structural barriers in capital intensity and profitability.

Progress requires regulatory change to allow lower-cost substrates, major reductions in energy needs for drying and climate-control, improved automation, and robust biosecurity systems. Co-located projects with secure substrates and offtakes have the greatest chance of success in more niche markets. Additional barriers and constraints will need to be overcome in order for this food waste solution to truly reach mainstream potential.

Deep Dive: Biochar Feed Additives

Biochar is a carbon-rich material used as a feed additive that is made by pyrolyzing organic residues, thermally decomposing them in the absence of oxygen. When added to animal diets, biochar can improve gut health and nutrient use while sequestering carbon in stable form, offering a rare dual productivity-climate benefit. However, evidence of its feed efficacy is still emerging, regulation is incomplete, and adoption remains niche, keeping its promise largely prospective for now.

Pathway Overview

Inputs & Processing

Biochar can be produced from a wide range of residues and side streams, including wood chips, rice and corn husks, crop residues, and animal manures (Schmidt et al., 2019; Nair et al., 2023). These streams are pyrolyzed, heated to 400–700 °C in low-oxygen conditions (Khater et al., 2024), producing a stable carbon-rich material. This porous material is later ground into fine powders or microgranules that can be blended into animal diets (Kavindi et al., 2025).

Products

In feed applications, biochar is blended into mixed rations or premixes. It acts as an adsorptive additive that can carry probiotics, minerals, or fatty acids, survives digestion, and enriches manure by recycling nutrients and stabilizing carbon.

Target Markets

Trials have been conducted in ruminants, poultry, and swine to explore benefits such as improved gut health, weight gain, feed efficiency, toxin neutralization, and reduced methane emissions (Nair et al., 2023).

Commercial Viability

Status & Scale

Biochar as a feed additive is pre-commercial but growing. Global production was approximately 350K metric tonnes in 2023 (International Biochar Initiative, 2024), with animal feed as the second-largest application after soil (Allied Market Research, 2023). Commercial use is strongest in Germany, Switzerland, and Austria, with pilots across Europe, North America, and Asia.

Regionally, the EU has the clearest pathway, supported by the voluntary European Biochar Certificate (EBC), which sets safety benchmarks and has enabled scaling in Germany, Switzerland, and Austria. In the U.S., fragmented state-level rules are slowing adoption. China has a centralized approval process and is emerging as a leader, while Japan and other East Asian markets are in early stages of research and pilots.

Region	Regulatory Status	Commercial Status
EU & Switzerland	EU authorises vegetal carbon as a basic feed material (Regulation 2017/1017); EBC voluntary certification adopted by biochar manufacturers	Established use in Germany, Austria, Switzerland
U.S.	Fragmented, state-level rules; no federal definition	Pilot/demonstration use only
UK	Regulatory ambiguity (biochar is often classified as "waste")	Growing interest, early adoption
China	MARA oversees approvals for new feed ingredients; supportive policy environment	Early-stage commercial with rapid growth and strong R&D activity
Japan & Korea	No clear framework in Japan; South Korea supporting pilots via policy programs	R&D to pilot activity only
Rest of World	Limited approvals, fragmented frameworks	R&D and pilots only

Economics & Operating Costs

Estimated production costs for biochar for soil applications range from approximately $200–2,000 per MT (Zhang et al., 2021; Patel and Panwar, 2024; BioChar Daily, 2025), although this can vary significantly based upon the feedstock. Production cost estimates for feed applications are not readily available, although are likely toward the upper end of the range or higher, due to quality control and logistical requirements.

Operating cost drivers include:

- **Feedstock logistics:** Although abundant and inexpensive, biomass feedstocks are bulky, seasonal, and dispersed, leading to transport and preprocessing (i.e., drying, size reduction) dominating operating costs (Nematian et al., 2021).
- **Energy demand:** Pyrolysis is energy-intensive, requiring stable, high heat to ensure consistent throughput and product quality; capturing syngas and bio-oil co-products can offset energy use, with some facilities achieving near net energy self-sufficiency (Roberts et al., 2010).
- **Quality assurance:** Producing feed-grade biochar requires stricter contaminant controls and finer particle sizing than soil-grade biochar, adding cost.

Capital Expenditure (CapEx)

Biochar feed additives have not been produced at commercial scale. Thus, accurate CapEx data is unavailable.

Headwinds & Risks

- **Relatively high production costs:** Energy-intensive pyrolysis and strict contaminant controls for feed-grade biochar raise costs above soil-grade uses.
- **Regulatory uncertainty:** In many regions, biochar is still classified as "waste," complicating scale-up and limiting formal feed additive approvals.
- **Performance variability:** Animal nutrition benefits remain inconsistent across trials, with outcomes dependent on feedstock, processing, and dosage; this uncertainty is slowing adoption.
- **Logistics & feedstock challenges:** Biomass feedstocks are bulky, seasonal, and dispersed, making transport and preprocessing costly.

Tailwinds & Opportunities

- **Dual revenue potential:** Biochar can combine animal productivity benefits with carbon sequestration, creating both feed value and potential carbon credit income streams.
- **Regulatory progress:** Authorization in the EU under Regulation 2017/1017 establishes a legal baseline for feed use.
- **Premium market access:** Certification schemes such as the European Biochar Certificate "EBC-Feed" guideline may enable access to higher-value markets by demonstrating quality and safety.

Environmental Impact

Biochar stands out as a feed additive that also delivers carbon removal, with potential to sequester carbon for centuries when applied to soils post-excretion from biochar-fed livestock. The environmental impact comes from its ability to reduce emissions from ruminants, and utilize waste materials.

System Dependencies

Environmental outcomes depend on feedstock sourcing, pyrolysis design, and certification. Without strict quality control, benefits can be undermined by contaminants and inconsistent performance.

Impact Area	Findings
Climate Change	Each metric tonne of stable carbon in biochar represents approx. 2.7 MT CO_2-e sequestered (International Biochar Initiative, 2024); enteric methane reductions of 0–21% have been observed in ruminant diets (Ni et al., 2024; Qomariyah et al., 2022); pyrolysis emissions can be offset by using syngas and bio-oil co-products as fuel (Peters et al., 2015).
Land & Water	Biochar use does not directly cut land or water demand as it serves as a feed additive, rather than replacing feed; however, biochar-enriched manure improves soil nutrient retention, reducing runoff and enhancing fertilizer efficiency.
Nutrient Cycling & Air Quality	Adding biochar to feed reduces ammonia and hydrogen sulfide emissions from barns by >15%, improving animal welfare and air quality (Chen et al., 2021; Banik et al., 2021); it also stabilizes nitrogen and phosphorus in manure, strengthening nutrient cycling.
Risks & Certification	Poorly produced biochar can contain PAHs or heavy metals, requiring strict quality control; the European Biochar Certificate (EBC) sets feed-specific thresholds to ensure safety.

Case Studies

CharLine | *Austria*

CharLine, an Austrian company, is a dedicated, livestock-focused producer that has built a successful business by adhering to strict quality standards. Their "FeedChar" product line, explicitly sold for cattle, pigs, and poultry, holds certifications such as EBC-Feed and GMP+. Publicly available data sheets confirm rigorous contaminant testing, providing a crucial layer of trust for farmers. This case study demonstrates how a well-defined regulatory and certification framework is a powerful enabler of a commercial biochar market (CharLine GmbH).

Animal-type-specific product lines | *Ireland & Switzerland*

The Feedchar Company in Ireland and several producers in Switzerland, including Swiss Biochar and LignoCarbon, have developed specific product lines for different animal types, such as AgriChar for cattle and EquiChar for horses. They source spent brewer's grain and pyrolyze it into biochar. This highlights a viable commercial strategy focused on product differentiation and targeted customer solutions (The Feedchar Company).

Outlook

Biochar is attracting attention as a feed additive because of its potential to deliver dual benefits: improving animal productivity while offering durable carbon removal. In theory, it could reduce methane emissions, recycle nutrients, and generate carbon credits—creating both climate and financial upside. Yet the market remains fragmented and early stage, with biochar sitting at an estimated TRL of 5–6 and only limited global production capacity.

Realizing this potential will require overcoming key hurdles. Production costs remain high, regulatory frameworks are inconsistent across regions, and quality assurance is critical since poorly produced biochar can introduce contaminants. Demonstrating consistent results—such as multi-site trials proving significant reductions in methane production or measurable productivity gains in biochar-fed livestock—will be essential to secure formal approval and market confidence. If these barriers are addressed, biochar could shift from a niche innovation to one of the rare feed solutions capable of combining animal performance benefits with durable, verifiable climate impact.

Conclusion

Current waste-to-feed pathways embody a spectrum of maturity, scalability, and regional applicability. Mature systems such as brewers' spent grain and former-food meals are already well established and commercially stable. They provide reliable options, but their future growth is constrained by limited feedstock volumes and market saturation.

In contrast, innovative and underutilized pathways present a dynamic, albeit less certain picture. Single-cell proteins appear to stand out with a relatively clear trajectory to scale, particularly in aquafeed and pet food, provided that energy integration, feedstock access, and regulatory approvals are secured. Insect farming has attracted significant investment but continues to face challenges including high costs, regulatory restrictions, weak environmental performance, and an inability to utilize food waste beyond items already authorized in conventional livestock feeds, potentially limiting its near-term role. Swill is proven in Asia, where it is supported by policy and infrastructure but remains restricted in Europe and the U.S. Finally, biochar feed additives occupy an emerging niche, offering both potential animal productivity benefits and carbon sequestration, though high production costs, uncertain technical performance, and uneven regulation need to be overcome.

Taken together, these approaches underscore both the diversity and the potential of waste-to-feed pathways. Even if no single pathway offers a universal solution, collectively they point to meaningful opportunities to reduce disposal costs and potentially displace carbon-intensive feed crops and fishmeal, as well as improve resource efficiency across supply chains. For businesses, adoption decisions will depend on proximity to feedstocks, logistics feasibility, and regulatory frameworks. For funders, the choice is between backing established models with incremental gains or engaging with newer approaches that carry higher risk but the potential for long-term impact.

By aligning investment and adoption strategies with pathway characteristics, funders and businesses can help advance the most promising new waste-to-feed pathways from alternatives to established pillars of a more circular food system.

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Acknowledgements

The Centre for Feed Innovation (CFI) is a think tank dedicated to advancing sustainable, scalable, and safe alternatives to conventional animal feeds. CFI works across science, industry, and finance to accelerate innovation in feed systems that reduce environmental impacts and strengthen global food security. Through independent research and collaboration, CFI provides analysis and advice that support evidence-based decision-making across feed innovation, policy, and investment.

CFI

About ReFED

ReFED is a U.S.-based nonprofit that partners with food businesses, funders, solution providers, policymakers, and more to solve food waste. Its vision is a sustainable, resilient, and inclusive food system that makes the best use of the food we grow. The organization serves as the definitive source for food waste data, providing the most comprehensive analysis of the food waste problem and solutions to address it. Through its tools and resources, in-person and virtual convenings, and services tailored to help businesses, funders, and solution providers scale their impact, ReFED works to increase adoption of food waste solutions across the supply chain. To learn more about ReFED and solutions to reduce food waste, please visit www.refed.org.

Learn more about ReFED's Capital & Innovation programs and resources for funders like our *Food Waste Funder Circle* by contacting Sharyn Murray:

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