Implementing Biochar in the Fraser Valley

FINAL REPORT

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Study 2. (S2) Yuan, Y, Chen H, Yuan W, Williams D, Walker J T, Shi W. Is biochar-manure co-compost a better solution for soil health improvement and N2O emissions mitigation? Soil Biology and Biochemistry. 2017. 113, 14–25. https://doi.org/10.1016/j.soilbio.2017.05.025

Study 3. (S3) Hangs RD, Schoenau JJ, Knight JD. Impact of manure and biochar additions on annual crop growth, nutrient uptake, and fate of 15N-labelled fertilizer in two contrasting temperate prairie soils after four years. Canadian Journal of Soil Science. 2022. 102(1), 109–130. https://doi.org/10.1139/cjss-2021-0006

Study 4. (S4) Harrison BP, Gao S, Gonzales M, Thao T, Bischak E, Ghezzehei TA, Berhe AA, Diaz G, Ryals RA. Dairy manure co-composting with wood biochar plays a critical role in meeting global methane goals. Environmental Science & Technology. 2022. 56(15), 10987–10996. https://doi.org/10.1021/acs.est.2c03467

Chapter 1: Manure management in the Fraser Valley

Chapter Summary, The Fraser Valley is one of Canada's most agriculturally intensive regions, generating over 2.7 million tonnes of manure annually, mainly from dairy and poultry farms. However, limited land availability, nutrient overloads, and changing climate conditions have made manure management a growing environmental concern, particularly regarding water contamination and greenhouse gas emissions (GHG). Manure exists in varying forms and nutrient concentrations depending on livestock type, moisture levels, and handling practices, which complicates storage and land application strategies. Despite strict seasonal restrictions and infrastructure requirements under British Columbia's Agricultural Environmental Management (AEM) Code, challenges like restricted land access, rising costs, and labour shortages persist. While some farms are adopting strategies like composting and infrastructure upgrades, adoption remains uneven and complex. Meanwhile, the region generates a diverse supply of other organic residues, including but not limited to food, yard, and forestry waste. These wastes, along with manure, have feedstock potential, offering a more circular, climate-resilient approach to organic waste management.

The Fraser Valley of British Columbia is one of Canada's most intensively farmed areas, particularly recognized for its abundance of dairy and poultry farms [60,63]. These operations contribute significantly to the province's organic waste stream, with livestock farms in BC generating approximately 2.7 million tonnes of manure annually - 65% from dairy, 17% from poultry, and 14% from swine [65]. In this highly productive yet small area, managing manure poses environmental and logistical challenges. Decades of intensive poultry and dairy farming have resulted in heavy nutrient loading on little land, especially in sensitive zones such as the Abbotsford aquifer [63,64]. If not managed properly, manure can introduce pathogens, antibiotics, and heavy metals into ecosystems, leading to nutrient leaching, eutrophication, and soil degradation [12,66]. These issues are amplified by climate change, which is expected to intensify precipitation and alter nitrogen cycling in the region [60]. At the same time, manure remains a valuable resource with the potential to enhance soil health and support circular nutrient systems [12,66]. Strengthening manure management in the Fraser Valley is therefore not only an environmental necessity but also an important step toward regenerative and climate-resilient agriculture [62].

This location is home to some of the most productive soils, primarily composed of fine-textured, fertile deposits from glacial and post-glacial floodplains [113]. These lowland soils, including the Monroe and Ladner series, are rich in clay and silt, providing good water retention and nutrient-holding capacity that support intensive farming [113]. The region's soil nutrient levels have shown elevated concentrations of nitrogen and phosphorus in certain areas, posing environmental risks such as nitrate leaching and phosphorus runoff to nearby water bodies [112]. Soil types vary across the Fraser Valley, with common classifications including Brunisols, Gleysols, Podzolics, and Regosols, reflecting diverse parent materials and drainage conditions [114,115]. This diversity influences how nutrients and water move through the landscape and affects agricultural management practices.

The Fraser Valley's livestock industry, primarily chickens and cattle, is responsible for the majority of the region's manure production. While other livestock such as sheep, goats, mink, and horses contribute to the organic waste stock, these animals collectively account for only about 21% of manure from their respective types [67]. In contrast, most of the cattle manure in Southwest British Columbia (SWBC) originates from dairy farms, whereas beef cattle - responsible for a significant portion of manure at the provincial level - are largely located outside of the region [67].

Manure in the region exists in multiple physical forms, primarily influenced by livestock type, moisture content, and management systems [67,71]. Dairy manure usually varies between thick slurries to highly diluted liquids with moisture content exceeding 90%, especially in barns that rely heavily on water for cleaning and animal drinking [67,76]. Solid manure, typically produced by poultry operations or dairy barns that use bedding, has a lower moisture content and can be easily stacked and stored [67,71]. Normally, solid manure has moisture levels below 80%, semi-solid (or slurry) manure falls between 80 - 88%, and liquid manure surpasses 88% moisture [71]. These characteristics dictate how manure is handled, stored, and applied in British Columbia.

Nutrient composition in manure varies considerably depending on moisture levels, livestock diets, bedding additions, storage conditions, and sampling methods [67,76]. Manure is an important source of nitrogen (N), phosphorus (P), potassium (K), and sulphur (S), as well as macronutrients like calcium (Ca) and magnesium (Mg) [75]. Studies in BC have shown that ammonium concentrations tend to peak in dairy manures with 94 - 96% moisture, while other nutrients are often more concentrated in drier manures [67]. However, this variability complicates nutrient management planning.

Storage and treatment systems for manure vary across operations. Liquid manure is typically contained in concrete tanks, lagoons, or earthen basins, while solid manure is stored in uncovered or covered piles, either on pads or directly on soil [71]. In BC, farms are generally expected to maintain 6 to 7 months of storage capacity to account for seasonal restrictions of application, particularly in high-precipitation regions like the Fraser Valley. Manure application is restricted from November through January, and requires risk assessments for spreading during October, February, and March [68,70]. These restrictions are intended to reduce nutrient runoff and protect water quality, but they further increase pressure on farms to store manure for extended periods - those of which also hold safety restrictions.

Land application remains the most common use of manure, particularly on forage crops, although synthetic fertilizers are used more often [61]. However, with the rising costs, urban sprawl, and decreasing availability of land, farmers in the Fraser Valley are having a difficult time distributing manure effectively [60]. Thus, the management of manure has cascading effects on local ecosystems and urban environments. In response, farms are exploring strategies such as leasing additional land, exporting manure to other farms, separating solid and liquid fractions for easier transport, composting to reduce volume and odour, and expanding or covering storage facilities [68]. Each of these options comes with their own financial, technical, and regulatory concerns. A variety of manure handling systems are used in the region, including gravity-flow channels, circulatory agitation tanks, and daily scraping with tractors [72-74]. The choice of system depends largely on farm layout, available labour, and operational scale. Regardless of method, all systems must comply with the Agricultural Environmental Management (AEM) Code, which outlines strict requirements for storage design and duration to minimize environmental risks [69].

Figure 1: Hoop frame storage for solid agricultural waste, A covered structure used for manure, urine, bedding, and other biological wastes, typically cleaned out from animal pens and stalls (BC Ministry of Agriculture, 2015).

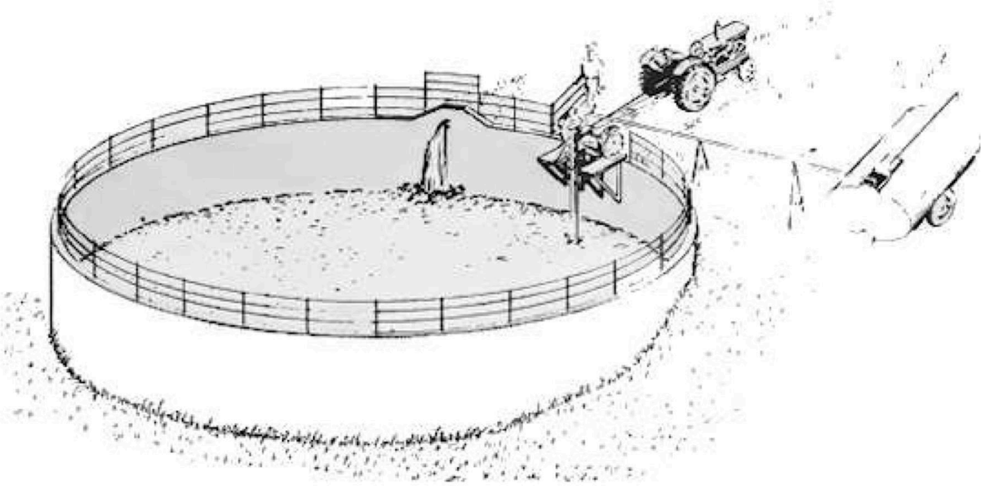

Figure 2: Below-ground circular manure tank, Subsurface storage system for both solid and liquid manure, designed to minimize disturbance and reduce odor and emissions (Agriculture Canada, 1981).

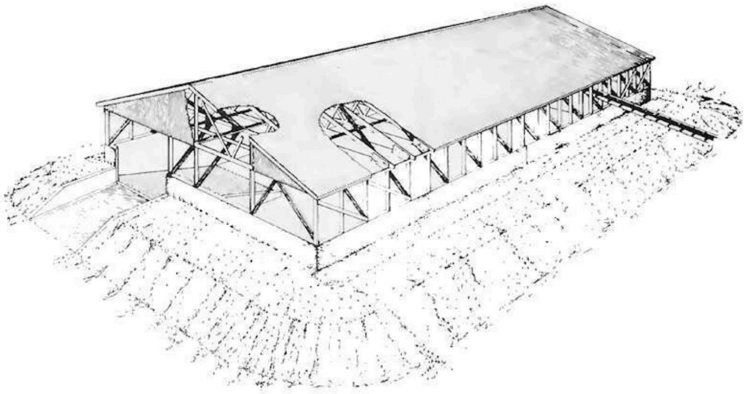

Figure 3: Rectangular roofed storage for semisolid manure, Concrete storage facility for solid manure, with multiple input options and an open-ended design that allows for gas release (Agriculture Canada, 1981).

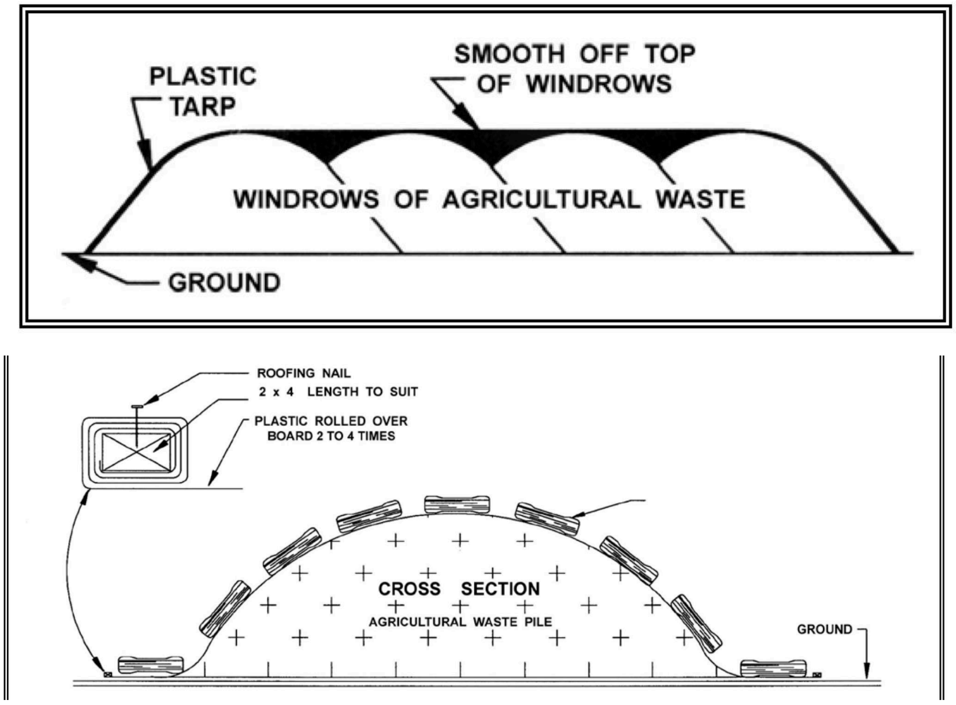

Figure 4: Windrow storage of agricultural by-products, Field-based system for storing and composting solid farm wastes in elongated piles, requiring compliance with agricultural standards to prevent leaching into aquifers (BC Ministry of Agriculture, 2015)

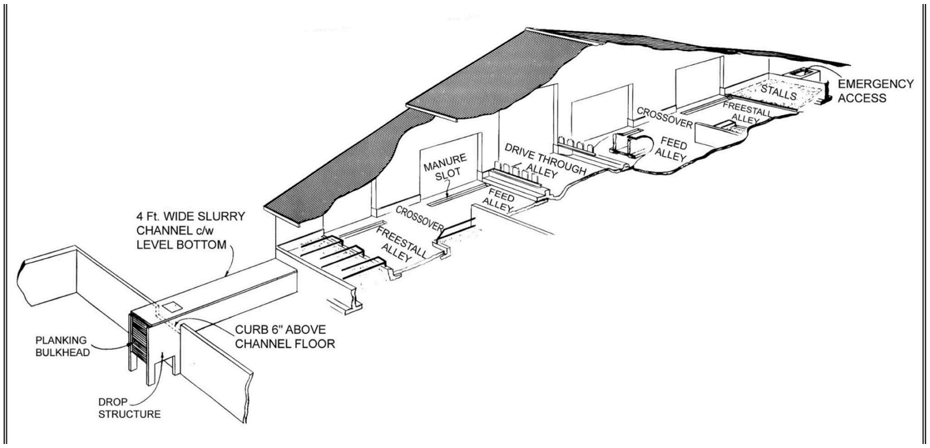

Figure 5: Gravity flow slurry channels, A simple and reliable system designed exclusively for liquid manure (slurry), unsuitable for solids or bedding (BC Ministry of Agriculture, 2015).

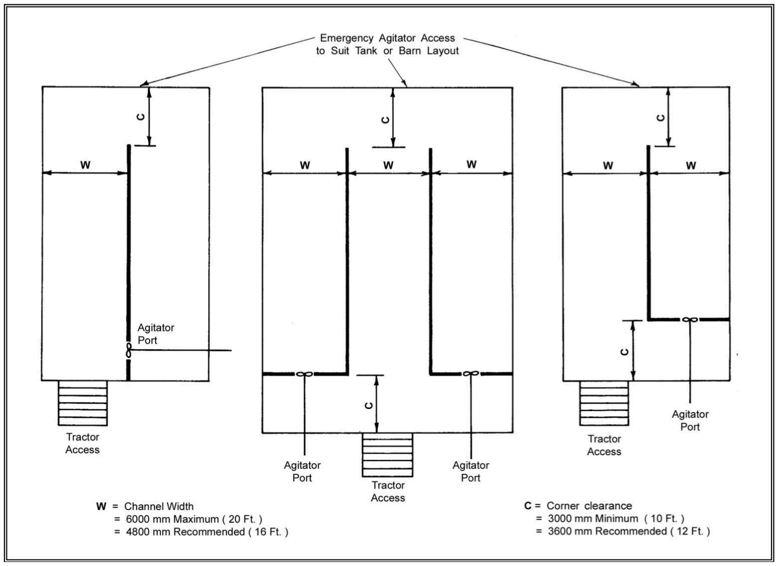

Figure 6: Circulatory agitation system for concrete dairy manure tanks,Storage and mixing system for both solid and liquid manure, requiring monthly agitation and allowing for same-day field application (BC Ministry of Agriculture, 2015)

The diversity of manure forms, variability in nutrient content, and regional limitations on land and storage infrastructure make it difficult to manage manure in the Fraser Valley. These challenges make it a necessity to investigate new improvements in infrastructure and technology. While the Agricultural Environmental Management (AEM) Code has mandated standards for storage and application, the ability to successfully follow regulations is influenced by access to financial and technical support [77]. Opportunities like the Manure Storage Expansion Program (MSEP), which covered up to 20% of capital costs for storage infrastructure, have supported at least 85 Fraser Valley farmers [77]. Similarly, the Sustainable Poultry Farming Group (SPFG) has helped relocate poultry manure away from the Abbotsford aquifer and promoted groundwater protection through nutrient redistribution programs [77].

However, improved infrastructure alone does not ensure better practice. Adoption remains uneven across the region, in part due to cost, inadequate labour force, and limited farmland access [77,78]. To help overcome these challenges, a few recent initiatives have begun. A mobile centrifuge system designed to extract phosphorus from dairy manure is being piloted in Chilliwack and Abbotsford, while plans for a community-scale anaerobic digester could process manure from over 1,000 cows and 1 million chickens [79].

In addition to manure, British Columbia generates a wide variety of organic residues. Between 0.6 and 4.7 million oven-dry tonnes of forestry harvest residues are wasted each year in BC, the majority of which is burned on-site to reduce wildfire risk [81-85]. Metro Vancouver alone diverted 161,309 tonnes of wood and 401,890 tonnes of food and yard waste from disposal in 2021 [86]; yet, organic waste still accounts for 40% of landfill waste across the province [89]. Agricultural sectors also produce a substantial volume of feedstock [87]. For example, berry producers in the Fraser Valley generate up to 64,000 tonnes of pruning waste and 69,000 tonnes of spoiled product annually [87], alongside significant volumes of livestock manure [88]. Although some of these residues are rich in fibre and present processing challenges, pyrolysis offers a promising route for transformation [87].

Chapter 2: Biochar’s Manure Nutrient Transformations

Chapter Summary, This chapter explores the integration of biochar into manure management systems, particularly within the context of the Fraser Valley's agricultural landscape. Biochar’s beneficial properties make it an effective soil amendment that can enhance nutrient retention, support microbial activity, and reduce nutrient losses in the aquifer. The chapter emphasizes how biochar’s effectiveness depends on variables such as feedstock type, pyrolysis temperature, application rate, and timing of integration. Three primary strategies for manure-biochar integration are outlined: (1) pyrolyzing manure directly to produce biochar, (2) charging plant-based biochar with manure slurry, and (3) co-composting biochar with manure and local organic waste. Each method presents specific advantages and challenges. The chapter also addresses how biochar's interactions with clay minerals can further enhance carbon stability and nutrient retention.

Biochar’s adoption as a soil amendment is due to its appealing physicochemical characteristics, including porosity, surface area, pH, cation exchange capacity (CEC), and functional groups that facilitate nutrient sorption and retention [2,24]. Produced by pyrolysis, biochar is typically carbon-rich and highly porous, allowing it to adsorb positively charged ions such as ammonium (NH_4^+), potassium (K^+), and calcium (Ca^{2+}) [17]. Therefore, the structure allows it to act as a slow-release nutrient reservoir, enhancing plant nutrient availability while reducing leaching losses [17]. Simultaneously, this porosity of biochar causes it to host beneficial microbes that support soil biochemical processes - for instance, nutrient and carbon cycling [97]. Together, these features make biochar particularly promising for improving soil health and manure management in agricultural zones like the Fraser Valley.

Biochar’s performance as a soil amendment is dependent on its creation and application characteristics. One of the most influential is feedstock type. Biochars derived from plants and manure offer different nutrient profiles and sorption capacities. Manure-based biochars tend to have higher concentrations of macronutrients (nitrogen, phosphorus, potassium), ash content, and reactive surface sites [49,99-102]. Plant-derived biochars have reactive oxygen-containing functional groups that contribute to their nutrient retention, and this effect can be further increased when they are charged with substances like manure slurry [50,98,103-105]. Another important factor is pyrolysis temperature. Biochars produced at high temperatures (400 - 600℃) tend to have greater carbon stability, structural integrity, and NO_3^- content, but reduce yield, NH_4^+ sorption, and total nutrient content due to volatilization [17,18,106,107]. Lower-temperature biochars (200 - 400℃), on the other hand, maintain more oxygen-containing functional groups, improving retention of ammonium and enhancing microbial activity [21]. These conditions result in biochars with relatively high carbon content and pH [17,106,107].

The timing of biochar integration within the manure management system also significantly affects its effectiveness. Biochar can be added at several stages: during animal bedding, co-composting, anaerobic digestion, or mixed directly with liquid manure before land application [23,50,51,54,55,59]. Each point of integration has its various benefits. For example, adding biochar to bedding reduces ammonia emissions [50,51], while co-composting increases microbial activity and accelerates the compost’s maturity [23,52,54].

Recent research shows that clay minerals improve long-term carbon stability and enhance nutrient retention when mixed with biochar. When biochar is applied to clay-rich soils, such as kaolinite and montmorillonite, the formation of organo-mineral complexes can inhibit oxidation of interior carbon structures, thereby extending biochar’s persistence in soil systems [108-110]. These improvements were linked to transformations of aromatic $C - C/C = C$ bonds into more stable ester ($C - O$) and methyl ($C - H$) configurations that encourage bonding with aluminum groups in clay [108]. Additionally, interactions with clay minerals increase pore diameter due to cation insertion (e.g., Ca^{2+}, Al^{3+}) and stabilize soluble organic fractions through ligand exchange with Fe/Al oxides [108]. These organo-mineral associations enhance carbon retention and can modify surface area and reactive groups, depending on biochar particle size [109].

The biochar application rates and the soil and crop contexts are critical regarding the potential for improving soil quality [48]. In a study by *Yang et al.*, lower application rates of 600 to 900kg/ha (or, 0.6 to 0.9 t/ha) benefit plant growth, soil fertility, and accumulation of nutrients [92]. However, a surplus of application can have a negative impact, such as heavy metal exposure, excessive nutrient accumulation, or increasing soil nitrous oxide emissions [92,95,96]. Therefore, recommended application rates depend on biochar and soil characteristics [93].

The Fraser Valley region's surplus of slurry manure makes it a strategic location for evaluating biochar's role in nutrient recovery, emissions reduction, and sustainable land application. The following paragraphs describe three feasible strategies for biochar-manure integration: using manure as a biochar feedstock, charging plant-based biochar with slurry, and composting manure and biochar together. **Table 1** highlights real-world projects that incorporate biochar into one of these three categories, and summarizes their outcomes.

Table 1: Biochar Feedstocks and Outcomes

Study ID	*Feedstock*	*Pyrolysis Temperature*	*Manure Type Tested*	*Set-up (Lab column, pot, field)*	*Application Rate (t/ha)*	*Outcomes* ** GHG outcomes: % ↑/↓ or kg CO_2 or N_2O* ** Nutrient leaching: kg N or P retained/ha* ** Carbon storage: t C/ha or % ↑ SOC* ** Microbial Activity: ↑/↓*
S1	-	-	6 Week Old Dairy Manure	Side-by-side cement block enclosures; treatments included biochar-compost mix (with wood vinegar + water) vs. control. Biochar-compost retained more moisture, while control heated faster and reached higher peak temperature	~20% v/v biochar (compost mix)	↑ C:N ratio compared to control
S1	Boiler Ash	-	Cattle Manure	Randomized block design with three replicates (12' x 100' plots, no buffer strips).	Application rate was variable; least consistent for biochar +	↑ Biochar + manure treatment microbial activity (enzyme analysis)

				Treatments: control, biochar only, manure only, and biochar + manure. Biochar/manure applied over 7 days; plots grazed for 6 months; plant samples collected after 2 months; soil retested post-grazing	manure treatment due to mixture consistency	
S2	Rice Hull	“Low temperature gasification” for biochar 50-60℃ for compost	Chicken manure with bedding, composted with hardwood sawdust	Compost mixed with 1 L deionized water and incubated in perforated 10 L containers (turned 2-3x daily for 7 days). Four treatments (control, manure, biochar, manure+biochar compost) tested across three soil orders (4 treatments x 3 blocks)	-	↓ Cumulative N_2O emissions by 27 % in biochar + manure (BM) compared to manure-only (M) ↓ CO_2 emissions in BM ↓ Peak CO_2 flux rates in BM than M; cumulative 46-day CO_2 emissions ~35 % lower ↑ Soil organic C under both treatments, with BM showing greater and more stable gains
S4	85% Douglas fir and Ponderosa pine, 14-15% almond and walnut tree pruning, and <1% nutshells	Maximum pyrolysis temperature was reported to be 900 °C	Dairy manure (solid)	Field-scale compost windrow	0.91 t dry biochar / ~16.67 t feedstock total (~5.5% w/w)	CH_4↓ 79%, CO_2↓ 19% Biochar C sequestration -215 kg CO2e / Mg manure, compost C sequestration -77 kg CO2e / Mg manure

The first strategy involves using manure directly as a feedstock for biochar production. When manure is pyrolyzed, the resulting biochar has heightened levels of nitrogen, phosphorus, and potassium, making it a nutrient-rich soil amendment [49,99-101] This type of biochar also tends to have high ash content and more active surface sites for nutrient sorption, contributing to improved plant growth and reduced reliance on synthetic fertilizers [102]. In anaerobic digestion systems, adding 10 g/L of manure-derived biochar can increase methane yield by up to 35% while decreasing microbial buffer times [55,59]. However, manure feedstocks present logistical challenges. Slurry must be dried or pretreated before pyrolysis, and if not processed properly, the biochar may contain heavy metals or antibiotic residues [9,10,25]. However, in the context of the Fraser Valley, manure-derived biochars with elevated calcium content have potential to immobilize heavy metals through ion exchange [110,111]. Lastly, high-moisture feedstocks can result in lower carbon yields and higher processing costs. Despite these trade-offs, manure-based biochar represents a promising method of waste management.

The second strategy is charging plant-derived biochar with liquid manure, prior to application. In this approach, plant-based biochars - potentially produced from locally available wastes - are soaked in slurry, allowing them to adsorb key compounds like ammonium and phosphate [22,50,98,99,100-105]. This method benefits from the structural integrity and high surface area of plant biochar while leveraging the nutrient density of dairy manure. Studies show that this method creates nutrient "hotspots" in soil, improves microbial activity, reduces leaching, and allows for slow nutrient release over time [5,8,10-13]. Small amounts of biochar (e.g., 1%) that are charged with manure have been shown to reduce NH_4^+ and PO_4^{3-} loss by 43% and 65%, respectively, while lowering emissions of N_2O and CO_2 [58]. However, this strategy requires infrastructure that supports manure storage, collection, and biochar soaking. Nonetheless, when properly implemented, this method can significantly reduce nutrient losses and greenhouse gas emissions.

The third strategy is composting biochar with manure and other organic materials before field application. Co-composting allows biochar to stabilize organic matter, reduce nitrate leaching, and improve compost maturity [23,94]. For example, research has shown that composts containing biochar and manure can significantly outperform standard composts in terms of germination and crop growth rate, biomass production, pH levels, improve humic-to-fulvic acid ratios, suppress nitrification and ammonia volatilization, and increase soil chemical characteristics (20,48,50]. When properly balanced, this method also reduces nitrate leaching and enhances soil microbial activity [20]. Studies have shown that biochar can effectively absorb key macronutrients found in dairy manure. For instance, the co-adsorption of ammonium and phosphate onto biochar surfaces has been demonstrated to improve nutrient loading efficiency [22]. In terms of GHG emission reductions, co-composted biochar can reduce N_2O emissions by up to 84% and NH_3 emissions by around 65% [52,54], although these outcomes are dependent on application method and compost ingredients. However, composting requires space, time, and turning infrastructure. Additionally, when using manure, further processing may be necessary, such as separating solid and liquid fractions, to ensure effective co-composting, although the literature does not always specify these steps [92,95,96]. The ratio of biochar to organic matter must also be optimized to avoid nutrient imbalances or phytotoxicity. Despite these logistical considerations, co-composting remains one of the most accessible and scalable options for biochar integration on farms in the Fraser Valley.

Altogether, the effectiveness of biochar in agricultural systems depends on a complex interaction between feedstock selection, pyrolysis conditions, timing of use, and soil characteristics [53,56,57]. In a region like the Fraser Valley, where excess slurry, nutrient imbalances, and land pressures intersect, the integration of biochar into manure management offers an opportunity for sustainability and emission mitigation efforts. **Table 2** illustrates several projects that have successfully incorporated manure into biochar systems. These examples can serve as models for local producers looking to reduce emissions, improve nutrient cycling, and restore soil health using tailored biochar strategies.

Table 2: Charging Biochar with Manure

Study ID	*Biochar*	*Manure type*	*Experimental*	*Charging*	*GHG*	*Nutrient leaching*	*Noteworthy*

	Feedstock or Compost Ingredients		*set-up*	*strategy*	*effect*	*effect*	*Outcomes*
S1	Chicken manure + garden waste	On-farm animals; supplemented by donated manure; fermented	Pyrolysis conducted to 150 °F over 3 days	Combining Biochar and Manure	-	-	Pyrolysis successfully produced biochar from mixed manure and garden waste
S1	-	Cattle and equine manure, co-composted with other wastes	Biochar applied to small compost piles within windrows on-farm	Combining Biochar and Manure	-	-	Farmer reported ~2x increase in compost volume with biochar compared to previous production
S1	High-carbon boiler ash (used as biochar and liming agent)	Barn floor manure (winter accumulation)	Biochar added directly to winter barn floor piles; observed until September	Biochar applied to manure piles	-	-	Piles with biochar reached crumbly, soil-like consistency; piles without biochar remained wet and shrank ~50 %
S1	Mixed compost (hay, timber, vegetable garden, orchard)	Dairy manure and goat barn waste	Compost mixed with manure and biochar, placed in wire bins; reached 140 °F and stayed hot for weeks	Biochar incorporated directly into compost mixture	-	-	Piles maintained high temperature (~140 °F) for several weeks; finished compost had abundant earthworms
S1	-	Barn manure, added every few days	Two compost piles with different biochar rates (12.5 % and 3.6 %); temperature monitored	Biochar incorporated at two different rates directly into compost	-	-	Temperature slightly lower in 12.5% biochar pile vs control; slightly higher in 3.6% pile, indicating sensitivity to biochar rate
S1	-	Rabbit manure	Biochar added to manure pieces in worm bins, sometimes with EM-1	Biochar incorporated directly into worm bins with manure	-	-	Addition of biochar reduced ammonia odors and improved worm bin conditions; bedding became less compacted and more

			spray; multiple application methods tested	(varied methods)			aerobic, increasing productivity
S3	-	Liquid hog manure (LHM) and solid cattle manure (SCM)	Split-plot field experiment, two sites, cereal-oil seed rotation over four years; manure applied alone or with biochar	Biochar charged with manure and then applied	-	-	Synergistic effect of SCM + slow pyrolysis biochar enhanced N mineralization and water-holding capacity; fast pyrolysis biochar reduced crop growth and N uptake due to labile-C
S4	Biochar: Douglas fir + Ponderosa pine + prunings + nutshells Compost: dairy manure + orchard clippings	Dairy solid manure	Field-scale windrow	Biochar incorporated directly into compost mixture	$CH_4\downarrow$ 79% $CO_2\downarrow$ 19%		Biochar-compost reached maturity in 35 days; improved aeration and moisture control; potential for CH_4 mitigation at scale; stable C sequestration from biochar

Chapter 3: Introduction to Biochar as a Soil Amendment

Chapter Summary, Dairy farms in British Columbia's Fraser Valley face consequential challenges related to greenhouse gas (GHG) emissions, nutrient runoff, and nitrate leaching, largely due to high-moisture slurry manure. Biochar, a carbon-rich material derived from biomass and produced through pyrolysis, is emerging as a promising solution to mitigate environmental damages. Historically used by Indigenous communities, biochar enhances soil fertility and nutrient cycling when applied in low, targeted doses, especially when charged with dairy slurry. Its porous structure enhances nutrient retention, reduces leaching, stimulates microbial activity, and contributes to long-term carbon stabilization. Studies show biochar significantly reduces N_2O, NH_3, and CO_2 emissions during manure storage and field application, lowering overall GHG intensity. By supporting soil health and crop productivity, biochar aligns with Canada's sustainable agriculture goals and the characteristics of a Best Management Practice (BMP), particularly in regions with pressure with manure management like the Fraser Valley.

Dairy farms in the Fraser Valley play a significant role in British Columbia's agriculture - as well as are a substantial contributor to concerns around greenhouse gas (GHG) emissions, nutrient runoff, and nitrate leaching. The region's volume of high-moisture slurry manure presents ongoing management challenges, especially during spring, when leaching risks peak [34,35]. Emissions of CO_2, N_2O, and NH_3 from manure storage and field application further intensify environmental pressures (14). Addressing these issues requires strategies that improve both soil function and nutrient cycling, all while reducing the region's agricultural GHG emissions.

One emerging tool with the potential to meet these goals is biochar: a porous, carbon-rich material produced from pyrolysis of biomass. Initially valued for enhancing plant growth and soil fertility, biochar also has the ability to mediate multiple soil processes simultaneously - specifically when utilized in low doses and charged with nutrient-rich substances like slurry [1,8,9,11,13,19,22,45]. Overall, it is globally appreciated for its potential in agriculture and environmental management [2,11].

Biochar isn't a new concept, it's been utilized as an ancient agricultural practice across the globe, where early farmers incorporated charcoal into soils to enhance fertility and crop productivity [28]. One of the most popular examples is Terra Preta de Índio - or Amazonian Dark Earths (ADE) - which were first documented by Portuguese explorers in the Amazon [28,29,30,32]. These fertile soils were cultivated by Indigenous Amazonian communities, their intentional practices included combining charcoal with organic materials such as manure, animal bones, fish residues, turtle shells, and pottery [29,30]. The origins of biochar use in ADE are estimated to date back at least 2,000 years [31,32]. While Terra Preta is the most cited historical example, similar uses of charcoal to enhance soil and yield have been documented among other Indigenous societies worldwide [33]. This holistic soil management method challenges the contemporary tendency to isolate each environmental challenge and prescribe independent solutions. Instead, they point to a multifunctional role for biochar, which plays a significant role in all aspects of soil and ecosystem health: increasing soil carbon storage, improving nutrient use efficiency, while maintaining overall yield.

Biochar's performance depends on how it is produced and applied. Low-temperature pyrolysis (300 - 400℃) retains more surface functional groups capable of adsorbing nitrogen [16]. However, biochars that are not created correctly can introduce contaminants into the amendment, including heavy metals and antibiotic residues [9,10,25]. Additionally, larger-scale applications may not be feasible due to feedstock restrictions, including transportation costs, seasonal variability in biomass supply, and land-use tradeoffs where biomass could otherwise support soil cover or habitat functions [33]. This reinforces the need for targeted, low-dose applications of biochar, developed for maximum benefit per unit of mixture.

When charged with dairy slurry, biochar's porous matrix absorbs nutrients and organic compounds, creating nutrient enriched hotspots within the soil [2,8,13,19,22,45]. These microenvironments have 3 significant characteristics: (1) they reduce the risk of leaching, typically associated with the field application of manure; (2) they retain important nutrients for slow release to plants and microbes; and (3) they stimulate microbial activity, accelerating the stabilization of organic compounds [9,11,13] and accelerates the breakdown of organic inputs into microbial byproducts [9,11]. The microbial byproducts of processed organic matter can combine with biochar surfaces or soil minerals, contributing to the formation of organo-organo or organo-mineral associations, which is a key mechanism for long-term carbon stabilization in soil [11,44]. This double role, acting both as a carbon sink and as a facilitator of soil aggregation and stabilization, makes biochar a uniquely powerful tool for increasing soil carbon stocks.

Biochar can reduce greenhouse gas (GHG) emissions from manure storage and soil application. A meta-analysis by *Cayuela et al.* (2014) reported an average 54% reduction in N_2O emissions - biochar type and application rate dependent. Additionally, composting with biochar has been shown to lower both N_2O and NH_3 emissions by up to 84% [15]. Ammonia volatilization can be reduced by 7%, depending on the age of the biochar [38], and by 25% when biochar is integrated with slurry manure during storage [39]. In terms of CO_2 emissions, biochar-amended soils have reduced their impacts by 7–8% [40], with reductions reaching up to 41% over two growing seasons [42]. Cumulatively, these mitigation effects contribute to an overall decrease in greenhouse gas intensity (GHGI) by at least 30% [37].

When implemented strategically, biochar aligns with Canada's goals for sustainable agriculture by improving soil health, increasing crop yields, and supporting carbon sequestration efforts [4,8]. In the context of agricultural Best Management Practices (BMPs), biochar is a promising strategy for farmers. BMPs in Canada aim to support both environmental and economic sustainability by encouraging techniques such as nutrient recovery, efficient manure handling, and erosion reduction [1]. Furthermore, biochar substrate can support the circular bioeconomy due to its nutrient adsorption properties, allowing for biowaste to be released safely back into the soils [11]. Biochar could become a widely adopted BMP by integrating it into manure management systems, especially in dairy-intensive regions, where nutrient surpluses and waste-related emissions are substantial challenges [3,5,6].

Chapter 4: Adoption of Biochar in the Fraser Valley

Chapter Summary, Dairy farmers in British Columbia's Fraser Valley face significant challenges from managing over 2.7 million tonnes of high-moisture manure annually in an area with limited land and sensitive ecosystems. Nutrient runoff, leaching into the Abbotsford aquifer, and greenhouse gas emissions from manure storage threaten environmental and farm sustainability. Biochar presents a practical, adaptable solution, particularly suited to the Valley's clay-rich soils. Its ability to bind nutrients, form stable organo-mineral complexes, and act as a slow-release fertilizer helps reduce nutrient losses, improve soil health, and lower pollution risks. Farmers can integrate biochar through direct application, slurry charging, or co-composting, fitting it into existing manure management systems and infrastructures. Research shows biochar can significantly cut nitrous oxide, ammonia, and carbon dioxide emissions, while also reducing odours and improving air quality. By decreasing manure volume, lowering transport costs, and enhancing composting efficiency, biochar also addresses economic and logistical constraints. In the Fraser Valley, using locally available organic residues - including cereal crop residues, orchard and vineyard prunings, greenhouse plant waste, and livestock manure - as feedstock for biochar production can support circular economy principles, reduce reliance on synthetic fertilizers, and provide long-term carbon sequestration. Overall, biochar could become a Best Management Practice, turning manure from a drawback into a valuable resource, and helping Fraser Valley dairy farms remain productive, law-abiding, and resilient in the face of environmental and economic pressures.

Dairy farmers in British Columbia's Fraser Valley face complicated challenges as they manage extensive quantities of high-moisture slurry manure in a region marked by limited land availability and sensitive ecosystems [60,63,65]. The Fraser Valley produces over 2.7 million tonnes of manure annually, primarily from dairy and poultry operations, placing immense pressure on the environment and farm infrastructure [65,67]. Nutrient runoff and leaching from these manures threaten the health of critical water bodies like the Abbotsford aquifer, while GHG emissions from manure storage and field application contribute significantly to the region's carbon footprint [12,14,36,63]. In this context, biochar appears as a potentially transformative amendment that addresses multiple interconnected problems faced by dairy farmers [1,2,5,7,13].

Biochar's unique physicochemical characteristics are well suited to the Fraser Valley's clay-rich soils [2,17,108,109]. These soils naturally retain nutrients and moisture but remain vulnerable to nutrient leaching when overwhelmed by manure [112,113]. If dairy farmers were to mix these fine-textured soils and biochar, their combination would form stable organo-mineral complexes that lock in carbon and nutrients, preventing them from washing away or volatilizing into the atmosphere [108-110]. This creates a unique relationship between biochar and the local soil orders, enhancing the soil health while mitigating the negative effects of surplus manure - in a way that few other amendments can.

For dairy farmers struggling with slurry manure that is both high in volume and moisture content, biochar offers practical and scalable solutions [67,71,72]. Whether through pyrolyzing manure directly to produce nutrient-rich biochar, soaking plant-based biochar in slurry to "charge" it with nutrients, or co-composting biochar with manure and other organic waste, farmers have full control over their biochar implementation style [22,49,52,99,100]. For instance, farmers with circulatory agitation tanks could potentially soak their biochar in slurry and apply it to their land [50]. Or, farmers could apply the biochar directly to their farm bedding, allowing a natural co-composting mixture to assemble [50]. These approaches not only help reduce the environmental risks associated with manure management but also transform what is traditionally seen as waste into a valuable resource [5,13,19]. Biochar charged with slurry acts as a slow-release fertilizer, improving nitrogen use efficiency, reducing leaching losses, and supporting microbial activity that further stabilizes organic matter [9,11,13,22]. This is crucial in the Fraser Valley, where seasonal restrictions on manure spreading and storage capacity constraints often lead to nutrient accumulation and elevated risk of pollution [68,70,77]. **Table 3** outlines the various manure management strategies that dairy farmers in the Fraser Valley can adopt biochar into.

Table 3: Management Types of Manure. Adapted from Sajeev et al., 2018

*Stage of Storage**	*Origin*	*Manure Type*	*Management Type*	*Benefits of Implementing Biochar*	*Management Description*
Housing	Biochar added to Bedding	All animal manure, any state	Sprinkle into bedding of animals	Reduced ammonia smell, soaks up liquid manure and creates soil-like compost, reduces swelling of compost, dryer stable, increased health of animals, reduced anaerobic conditions of bedding (S1)	Farmers have incorporated biochar directly into animal farm beds at varying levels, using any feedstock, though it is recommended to grind the biochar to improve handling and distribution.
Storage	Creating bins for compost	All animal manure, any state	Stored wastes and biochar into bins	Compost piles stay hot naturally for weeks, worm population abundant (S1)	Manure, plant wastes, and biochar are collected and placed into compost bins, with smaller bins recommended for better management. Some operations turn the compost periodically, while others leave it static depending on local practices and goals.
Field Application	Adding biochar to field windrows	All animal manure, any state	Composted biochar and manure into windrows	Produced double the biochar with smaller piles (S1)	Using small windrows, farmers can pile manure and biochar together and allow natural decomposition to occur. This method is less labor-intensive, and the outcomes depend on both the quantity of biochar added and the composition of the compost mixture.

The environmental benefits of biochar adoption extend beyond improved nutrient management. GHG emissions from manure storage and application, specifically nitrous oxide, ammonia, and carbon dioxide, create serious challenges for the region's climate goals and farm sustainability [14,36,90,91]. Studies show that biochar amendments can reduce nitrous oxide emissions by over 50%, ammonia volatilization by up to 25%, and overall soil CO2 emissions significantly [36,38,39,40,42] - depending on biochar type and application rate. These reductions not only help farmers reduce their carbon footprint but also improve air quality and reduce odours, enhancing farm conditions [14,15,37]. For dairy operations in the Fraser Valley, where environmental regulations are increasingly strict, biochar could be a Best Management Practice that helps farms meet regulatory standards while maintaining productivity [1,5,8].

Moreover, biochar's ability to improve manure handling and reduce storage volume addresses important logistical and economic concerns. Manure management in the Fraser Valley is hindered by rising land costs, labour shortages, and limited space for storage expansions, making innovative solutions necessary [60,77,78]. By incorporating biochar into manure systems, farmers can reduce the scale of manure applications needed, or the amount of spending on manure removal, therefore minimizing transport costs and easing pressure [13,68]. Additionally, biochar's role in composting accelerates organic matter maturation, improving the feasibility of on-farm composting programs that many dairy farms rely on [19,52,54].

Beyond immediate benefits, adopting biochar aligns with broader sustainability and circular economy goals important to British Columbia's agricultural sector [11,87,88]. In the Fraser Valley, several locally available organic residues could be options for biochar production. Crop residues such as corn stalks, wheat straw, and barley straw, orchard and vineyard prunings, greenhouse plant waste, and livestock manure can all serve as feedstocks. Utilizing these residues not only provides a sustainable source of biomass for biochar but also supports circular economy principles by recycling nutrients and carbon back into the soil [81-83,86,85]. This not only reduces reliance on synthetic fertilizers but also transforms agricultural waste management into an opportunity for climate change mitigation [11,80]. Biochar's exceptional carbon stability means it can lock carbon in the soil for thousands of years, contributing further to soil as an important carbon sink and helping farmers contribute to GHG reduction targets [11,44,80].

In conclusion, biochar offers Fraser Valley dairy farmers a feasible solution that tackles nutrient management, greenhouse gas emissions, soil health, and manure handling in one practice. Its compatibility with local soils, adaptability to diverse manure types, and potential to fit within existing farm infrastructure make it a realistic solution [2,5,13,108]. As pressures mount from environmental regulations, urbanization, and climate change, biochar could help make dairy farming sustainable in the Fraser Valley - transforming manure from an environmental liability into a valuable resource and enhancing farm resilience [1,13,77].

Chapter 5: Recommendations for Biochar Implementation in the Fraser Valley

Chapter Summary, This chapter provides evidence-based recommendations for implementing biochar as a BMP tailored to Fraser Valley dairy farms. Emphasizing cost-effectiveness and adaptability, it stresses a range of biochar production methods - from simple campfire pits to more sophisticated on-farm kilns - that fit diverse farm resources and commitment levels. Integration options vary from low-effort uses like bedding amendment to more involved processes such as nutrient capture and manure charging, offering multiple pathways to improve soil health, reduce emissions, and enhance nutrient cycling. Proper feedstock drying, kiln construction, safe handling,

optimal particle sizing, and storage practices are detailed to support effective and safe adoption. The chapter explains that biochar use is flexible and context-dependent, requiring farmers to match their goals, infrastructure, and labour availability. By presenting adaptable strategies alongside supporting tools and safety guidelines, this chapter aims to assist Fraser Valley farmers in incorporating biochar into their manure management sustainably and efficiently.

To support practical implementation of biochar as a BMP in the Fraser Valley, the following recommendations outline viable strategies tailored to local resources, established manure management practices, and environmental conditions. Each option considers different styles of manure involvement - production, charging, and application - and mentions potential co-benefits for soil health, water quality, and greenhouse gas mitigation. The intent is to provide adaptable, evidence-based solutions for farmers seeking to integrate biochar into their farming practices. **Table 4** summarizes a variety of feasible options for the dairy farmers in the Fraser Valley.

Table 4: Summarization of Biochar Implementation Strategies for the Fraser Valley

Biochar Type	Feedstock	Charging with Slurry (Y/N)	Biochar Implementation
Manure-derived	Manure	N	Combining with soil
Plant-derived	Wood	Y	Circulatory agitation tanks
			Gravity-flow channels
			Combining with soil
			Bedding
	Berries	Y	Circulatory agitation tanks
			Gravity-flow channels
			Combining with soil
			Bedding
Co-composting (Plant-derived)	Wood	Y	Circulatory agitation tanks
	Berries		Gravity-flow channels
	Bedding Straw		Combining with soil
	Plant-derived biochar		Bedding
Co-composting (Manure-derived)	Wood	N	Circulatory agitation tanks
	Berries		Gravity-flow channels
	Manure-derived biochar		Bedding

Local Co-composting (Plant-derived)	Wood	Y	Circulatory agitation tanks
	Berries		Gravity-flow channels
	Yard Waste		Combining with soil
	Food		Bedding
	Plant-derived biochar		
Local Co-composting (Manure-derived)	Wood	N	Circulatory agitation tanks
	Berries		Gravity-flow channels
	Yard Waste		Bedding
	Food		
	Manure-derived biochar		

Biochar adoption on Fraser Valley dairy farms presents an accessible, flexible, and scalable opportunity to enhance manure management and soil health without imposing excessive costs or infrastructure demands. As shown in Table 3, the versatility of biochar integration - from low-effort approaches like adding it to animal bedding to more involved processes such as adding biochar to agitation tanks - allows farmers to choose approaches aligned with their resources and operational type. The capacity to produce biochar on-farm using existing equipment, or even simple methods like in-ground campfires, makes this technology feasible for farms of varying scales and budgets. While higher investment in dedicated kilns and processing can yield superior biochar quality and volume, many farmers can start small and scale up over time, matching their available labour, funding, and commitment [116,117,119].

Utilizing biochar directly within barns to capture nitrogen as manure and urine are deposited offers a particularly efficient way to mitigate nutrient losses and reduce odours. This approach aligns well with Fraser Valley's diverse barn management systems, including pack barns where manure and bedding accumulate for extended periods before clean-out [50]. Farmers who incorporate biochar into barn floors or bedding report enhanced nitrogen retention and improved composting outcomes, suggesting immediate benefits without drastic changes to farm routines [50]. More advanced biochar production and handling strategies, such as pelletizing manure-derived biochar, can further improve storage, transport, and application logistics, addressing common challenges faced by Fraser Valley dairy farms related to labor, land availability, and environmental compliance [126]. However, these methods require greater initial investment, technical skill, and coordination, emphasizing the importance of tailoring biochar integration to farm-specific goals and pre-existing routines. Crucially, adopting biochar is not a one-size-fits-all process; farmers must weigh the costs and benefits relative to their existing infrastructure, manure handling practices, and environmental priorities

To support successful biochar implementation, attention to key operational factors - including feedstock preparation, kiln construction, safe handling, particle sizing, application rates, and storage - is important. The following sections explore these topics in detail, providing practical guidance and considerations for Fraser Valley farmers in adopting biochar as a BMP that complements their current systems.

Drying Feedstock

Drying feedstock prior to pyrolysis is a critical step in making biochar production more feasible for Fraser Valley dairy farmers. High moisture content in manure and other agricultural residues can significantly reduce pyrolysis efficiency, requiring more energy to evaporate water and lowering overall biochar yield [118,121,122]. Reducing moisture levels improves both the energy balance and the quality of the resulting biochar, as lower water content allows for higher process temperatures, more complete carbonization, and better sorption properties [122,123]. For farmers already managing nutrient-rich manure, on-farm drying can help incorporate biochar production without adding additional labour or costs to the operation [50,121].

Various drying strategies can be adapted to the Fraser Valley context to make this step more practical. Passive methods - such as sun-drying or using covered, non-sided storage containers - offer low-cost solutions during dry weather, while active systems like forced-air drying or utilizing waste heat from farm equipment or anaerobic digesters can accelerate drying year-round [121,129] Choosing the right method depends on factors like available space, on-farm preexisting infrastructure, and the scale of biochar production [50,124]. By adopting cost-effective drying techniques, dairy farmers can prepare feedstock efficiently, enabling consistent biochar production that supports manure management goals [125,127,128].

On-Farm Kiln Creation

Creating an on-farm biochar kiln can be a cost-effective and advantageous way for farmers to convert agricultural residues and manure into biochar. A commonly used design is the 55-gallon drum retort, which acts as the pyrolysis chamber where biomass feedstock is heated in the absence of oxygen [116]. The drum is sealed except for a vent pipe that allows gases to escape and ignite, producing a pyrolysis reaction [116]. This drum is typically housed inside a kiln made from insulating materials such as cement blocks or bricks to retain heat and improve energy efficiency during the process [116,117]. The feedstock inside the sealed drum is heated, causing it to remove gaseous volatile compounds, allowing the biomass to carbonize into biochar without combusting [116,117].

To build the kiln, certain materials and steps are mandated. For a standard kiln, key supplies include a drum with a lid, cement blocks of various sizes, fire bricks to protect the base, rebar for structural support, and a vent pipe made from thin-wall irrigation or muffler pipe, which requires welding skills for assembly [116]. The drum is supported inside the kiln on a sturdy metal frame, and fire bricks placed underneath help reflect heat and protect the ground [116]. The vent pipe should have precisely spaced holes to allow gas to escape and ignite safely [116]. To cover the kiln, rebar is threaded through blocks resting on the kiln walls, providing a stable, insulated lid [116]. Attention to these construction details helps ensure efficient heat retention and a safer, more effective pyrolysis process [116,117]. However, there are many instances where farmers have created biochar by utilizing a ditch-campfire situation [117]. Additionally, tremendous amounts of Youtube video, instruction manuals, and pamphlets are accessible online for free, each with various cost-friendly suggestions and blueprints. The more determined and committed the operation, the more promising the biochar produced.

Operating the kiln involves carefully managing feedstock size, moisture content, and airflow. Biomass should be dry (ideally below 25% moisture) and cut into pieces between 1 and 4 inches to optimize pyrolysis efficiency and char quality [120]. The kiln is initially loaded with loosely stacked medium-sized material at the bottom, topped with dry kindling to facilitate ignition [120]. The operator must manage the kiln by adding new layers of wood as the previous layers char, ensuring even heat distribution and preventing the charcoal from burning to ash [120]. This requires an abundance of readily available feedstock, as well as ample supervision.

As mentioned before, there are various simpler or more portable alternatives, such as inverted barrels with mesh lids, pit kilns, or flame cap kilns, which involve lighting biomass piles that burn from the top down in a controlled environment [117,119,120]. These methods can produce biochar with less upfront investment and technical skill but may be less efficient or produce variable char quality compared to insulated retort kilns [117,119]. Emerging commercial portable flame cap kilns, like those offered by Preta Carbon, provide affordable, transportable units that maximize biochar yield while minimizing smoke and emissions [129].

Handling, Beneficial Particle Sizes, and Application Rates of Biochar

Proper handling of biochar is essential to ensure the safety of farm workers and the effectiveness of its application. Because biochar dust is combustible and can irritate the skin, eyes, and respiratory system, personal protective equipment (PPE) such as gloves, masks or respirators, eye protection, and long-sleeve clothing should always be worn during handling and application to minimize exposure [119,130]. Managing dust by keeping biochar slightly damp, applying after charging with manure, or co-composting reduces the risk of airborne particles and combustion. Larger biochar pieces can be crushed using garden mulchers, ball mills, hammer mills, or even by running over the biochar with a lawn roller or vehicle to achieve a finer particle size [119,120]. However, operators should experiment with moisture levels when crushing biochar, as overly dry char creates excessive dust while overly wet char can clog machinery [120].

Particle size plays a critical role in biochar's performance in soil. Research shows that intermediate particle sizes, generally between 0.5 to 2 mm, optimize benefits such as plant growth enhancement and stress mitigation, including in saline soils [133,134]. Very fine particles (<0.063 mm) may suppress plant growth and reduce soil hydraulic conductivity by filling macropores, while larger particles (>2 mm) have less impact on water retention but may still benefit total soil porosity [132,134]. In coarse-textured soils, biochars with high intra-pore volume and hydrophilic properties improve water retention more effectively [132]. It is important to note that biochar properties such as hydrophobicity evolve with aging and weathering, which can influence its soil interactions over time [132]. Therefore, farmers should consider both particle size and biochar type to match their specific soil conditions and crop needs.

Determining the appropriate application rate is a flexible and often experimental process influenced by soil type, land goals, and biochar properties. Various online tools, such as the PNWBIOCHAR calculator and Pacific Biochar's worksheet, can assist farmers in estimating healthy biochar rates, although these tools have limitations and don't always incorporate site-specific characteristics [131]. Since biochar is diverse in composition and effect, many farmers rely on trial and error, applying smaller amounts initially [131]. Generally, biochar can be applied directly on the soil surface and allowed to incorporate naturally over time; there is little literature that favours any particular application strategy [132]. Farmers should avoid applying biochar in windy conditions to reduce dust exposure and handle it carefully to minimize airborne particles during transfer [130]. Combining appropriate handling, proper particle sizing, and carefully chosen application rates allows farmers to maximize the benefits of biochar as a soil amendment while ensuring safety and practical farm integration.

Testing Biochar

Before applying biochar to soil, it is essential to test its physicochemical and biological properties to ensure safety and effectiveness. Improperly produced biochar can contain elevated levels of heavy metals, polycyclic aromatic hydrocarbons (PAHs), furans, or dioxins [135,137]. Basic on-farm tests, such as seed germination assays using sensitive species or worm avoidance tests, can help detect potential toxicity and guide preliminary application decisions [136]. For more comprehensive and statistically analyses, biochar should be tested in accredited laboratories following standardized protocols that assess pH, nutrient content, carbon stability, and potential contaminants [135]. Each new feedstock, pyrolysis device, or operator change warrants fresh sampling, as variations in production conditions can affect biochar quality [135]. International frameworks such as the European Biochar Certificate (EBC) and the International Biochar Initiative (IBI) provide guidelines for proper testing, quality assurance, and certification, ensuring biochar meets recognized safety and performance standards before it is applied to soil [135-137]. Adhering to these testing practices is crucial because, once incorporated, biochar cannot be removed from the soil, making pre-application verification essential for environmental safety and long-term soil health.

Biochar Storage

Proper storage of biochar is essential for safety and maintaining its quality. It should be kept in a cool, dry place away from direct sunlight, food, and beverages to avoid contamination and degradation [130]. Freshly produced biochar can spontaneously heat and even ignite when exposed to air, especially in large quantities, so the volume and location of storage must be carefully managed to reduce fire risk [130]. Finely ground biochar dust is combustible if suspended in air within a closed container and exposed to an ignition source, making dust control important [130]. When repackaging leftover biochar, flexible bags are preferred over rigid sealed containers like cans or jars [130]. Although research on biochar storage is limited, keeping biochar in a cool, shaded area prior to application can be beneficial long-term.

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