Estimating the Environmental Impacts Associated with Dehydrated Poultry Manure Manufacturing in Eastern Canada Through a Life Cycle Assessment

by

Georgia Lewis

Submitted in partial fulfilment of the requirements
for the degree of Masters of Science

at

Dalhousie University
Halifax, Nova Scotia
April 2024

Dalhousie University is located in Mi’kma’ki, the
ancestral and unceded territory of the Mi’kmaq.
We are all Treaty people.

DEDICATION PAGE

<u>42</u>

This work is dedicated to my Mom (Jennifer), my Dad (Keith), my husband (Noel), my aunt (Sandi), my best friend (Kale), my dog (Bruno), and my cat (Joni Mitchell), as well as the real and forever living Joni Mitchell. Lastly, I would like to credit and dedicate this work to my late Nana Elva, who was always so supportive and incredibly encouraging of the Aggie path – this is for you.

Thank you and love always.

I would also like to dedicate this work to my supervisors, Andy and Goretty. You have enriched my life more than an enriched cage for a layer hen – more like a free-range pet hen. This journey has impacted every part of my life, and I am forever grateful for your support, kindness, knowledge-sharing, laughs, and patience. I feel thankful to have had both of you as supervisors and now friends (unless you are sick of me, which I understand).

No chickens were harmed during the making of this thesis. Except for those two roosters, they had to go…

Table of Contents

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Dehydrated poultry manure (DPM) is a pelleted form of poultry manure used as an organic fertilizer in agriculture, horticulture, and for home gardeners. The treatment of poultry manure can assist with effectively recycling it into a practical product that is easy to transport, store, and amend to soils. However, the environmental impacts associated with producing DPM have not been estimated. This research aims to estimate the environmental impact contributions of manufacturing DPM in Eastern Canada through a life cycle assessment (LCA). This analysis is a ‘cradle-to-facility gate’ LCA, including the sourcing, dehydrating, pelletizing, and packaging of DPM. Overall, the average global warming potential associated with manufacturing was estimated to be 299 kg CO_2-eq per tonne of packaged DPM. Other environmental impact categories were estimated per tonne of DPM to be 1.3 kg SO_2-eq for acidification potential, 0.7 kg N-eq for eutrophication potential, and 0.2 kg PM2.5-eq for respiratory effect. These impacts were primarily associated with the upstream impacts associated with poultry manure, manure drying, and the energy used in DPM manufacturing. Two key assumptions including the accounting for the upstream impacts of manure as a resource flow with a 50/50 Recycling approach and accounting for the biogenic carbon of a residual wood biomass, significantly contributed to global warming potential. Sensitivity analyses demonstrated these assumptions highly impact the baseline results. Further LCA studies should be conducted to better estimate the impacts of poultry manure as a resource in a value-added product and understand its potential impacts within the circular economy.

LIST OF ABBREVIATIONS USED

AP	Acidification potential
CE	Circular economy
CH_4	Methane
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
CPPL	Composted pelletized poultry litter
DAP	Di-ammonium phosphate
DPM	Dehydrated poultry manure
EP	Eutrophication potential
FAO	Food and Agriculture Organization
GA	Guaranteed analysis
GHG	Greenhouse gas
GLEAM	Global Livestock Environmental Assessment Model
GWP	Global warming potential
H_3PO_4	Phosphoric acid
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle inventory assessment
K	Potassium
K_2O	Potassium oxide
KCl	Potassium chloride
MAP	Mono-ammonium phosphate
MC	Moisture content
Mt	Mega tonnes
MOP	Muriate of potash
N	Nitrogen
N-eq	Nitrogen equivalent
NO	Nitrous oxide
NO_3	Nitrate
N_2O	Nitrous oxide
NO	Nitric oxide
OM	Organic matter
P	Phosphorus
P_2O_5	Phosphorus pentoxide
PM2.5	Particulate matter <2.5
PO_3	Phosphate
RE	Respiratory effect
RWB	Residual wood biomass
SDG	UN Sustainable Development Goals
SO_2-eq	Sulphate equivalent

ACKNOWLEDGEMENTS

The author would like to acknowledge Dalhousie's Faculty of Agriculture and Mitacs for supporting the project. We are thankful for the relationship and financial support of our two industry partners, Acti-Sol and Envirem, for their collaboration. A personal thank you to all the staff and owners of Acti-Sol and Envirem for their partnership and for making this research possible, including Claudia, Paul, Bob, Jim, and Yvano. All of you were helpful, engaged, and fun to work with despite your busy schedules. Thank you so very much. To Claudia and Yvano, thank you for the great days and tours of your facilities. They are great memories and so valuable. Another personal thank you to my fun and enthusiastic committee includes Andy Hammermeister, Goretty Dias, Peter Tyedmers, and Derek Lynch. I was fortunate to have you all. Thank you for the great conversations. Thank you to all my friends and family members for their unconditional love and support these last few years.

Chapter 1: Introduction

Dehydrated poultry manure (DPM) is a recycled nutrient source used for commercial agriculture, as well as market and home gardeners. Its widespread use is attributed to its slow-release delivery of essential nutrients, including nitrogen (N), phosphorus (P), and potassium (K), which promote plant growth as well as provide soil-enhancing benefits such as organic matter (OM) (Brunerová et al., 2020). Field trials conducted in Eastern Canada have yielded promising results for organic crop producers using DPM (Alam et al., 2018; Lynch et al., 2008; Sharifi et al., 2009). The increasing demand for DPM within the Canadian organic sector can be attributed to the limited availability of N fertilizers compliant with the Canadian Organic Standards (Andrew Hammermeister, personal communication, 2021). Additionally, DPM is a cost-effective method of distributing a valuable fertilizer product while supporting nutrient recycling in manure management systems (Ronga et al., 2020). With increased demand for DPM and increased awareness of the importance of evaluating the impacts of crop nutrients, it is important to estimate the environmental impacts associated with the DPM manufacturing process.

Life cycle assessment (LCA) literature relating to broiler and egg production identifies hotspots across shared environmental impact categories such as global warming potential (GWP), acidification potential (AP) and eutrophication potential (EP) (Costantini et al., 2021). The emissions associated with these impact categories are prominent in poultry LCAs due to the upstream emissions associated with fertilizer production and use required in growing crops for grain feed production, the manure management practices that cause ammonia (NH_3) emissions from barns and land application, and of manure application leading to nitrate (NO_3) leaching (Turner et al., 2022; Costantini et al., 2021; Pelletier et al., 2017; Leinonen & Kyriazakis, 2016; Pelletier, 2008). Although broiler and hen operations differ, these LCAs showcase the overall hotspots of the poultry industry.

The development and use of manure treatment technologies result from the increase in, and concentration of, livestock production in localized regions (Ronga et al., 2020; Peterson et al., 2013). Manure treatment methods include storage options until field application, composting for nutrient utilization, and energy recovery treatments from anaerobic digestion, gasification and pyrolysis. Estimating the environmental impacts of poultry waste treatment methods and their manufacturing processes, such as anaerobic digestion, gasification, and pyrolysis through LCA, has been completed (Kanani et al., 2020). Estimating the benefits of dehydrating and pelleting as a method of valorizing manure as a delocalized and sustainable organic fertilizer has been completed (Brunerová et al., 2020; Ronga et al., 2020). Poultry manure was found to be a suitable feedstock for yielding high-quality pellets. However, research estimating the environmental impacts associated with manure dehydration and pelletizing as a commercial fertilizer still needs to be understood. The following research proposes to address this gap by conducting a life cycle assessment of DPM manufacturing.

1.1. Introduction to Life Cycle Assessment Methodology

Life cycle assessment is a regulated methodology under the International Organization for Standardization (ISO) (ISO 14044, 2006) that evaluates environmental impacts associated with a product, process, activity, or whole system (Pelletier et al., 2015). To perform a process-based LCA, the material and energy flows are identified and quantified for each life cycle phase from extraction or access to raw materials ("cradle") to disposal ("grave") (Rebitzer et al., 2004). Material and energy flows include inputs at each stage (e.g., raw materials, intermediary products) and outputs (e.g., the primary products, co-products, waste, and emissions). Results from LCAs provide characterization and quantification of the environmental impacts of a product, process, or system over its lifetime (Pelletier et al., 2015). The results assist in identifying high-impact activities, also known as ‘hotspots,’ throughout the life cycle, allowing practitioners to compare the environmental impact of products, processes, or systems, as well as provide insights to improve efficiency, mitigate environmental risk when designing products, reduce waste, and avoid shifting problems to other activities or life cycle phases that could pose risks to people, society, and ecosystems (Sieverding et al., 2020). An LCA study consists of the following stages: goal and scope, life cycle inventory, life cycle impact assessments, and life cycle interpretation. The elements of these four stages are as follows:

I. Goal and Scope Definition: This phase outlines the proposed study's goal and scope, also known as the study parameters. The goal comprises communicating the study's precise question, intended audience, and application (Heijungs & Kleijn, 2001). The scope of study defines the function of the system and an associated functional unit (i.e., a quantitative unit of reference based on the function of the product or system) and the system boundaries (i.e., stages of the life cycle to be included). Additionally, methods for dealing with the environmental impacts of co-products are introduced in this phase as well as the selection of impact categories (e.g., GWP, ozone depletion, smog formation, or ecotoxicity), category indicators (e.g., 1 kg of nitrous oxide (N_2O) = 298 kg of CO_2-eq towards GWP), and the environmental impact assessment method (e.g., CML, TRACI, or ReCiPe).

II. Life Cycle Inventory (LCI): This is the accounting phase which involves collecting and organizing data regarding material, energy, and emissions associated with each product's life (Pelletier et al., 2015) and, more specifically, each activity (or process) associated with the product throughout its life cycle. Inputs and outputs associated with each product's life cycle are identified and quantified based on the functional unit (Rebitzer et al., 2004). Inputs include raw inputs from nature (e.g., water, minerals, timber, etc.) and inputs from the 'Technosphere' (e.g., electricity, packaging material, fuel, etc.). Similarly, outputs include products, co-products, wastes, and emissions to air, ground, or water. These inputs and outputs are referred to as flows in LCA terms.

III. Life Cycle Impact Assessment (LCIA): The LCIA is the subsequent step to the LCI in which further assessment modelling occurs and assesses the inventory data regarding contributions to environmental impact categories. At this phase, inventory results are quantified in relation to the selected environmental impact categories, calculation of impact categories (characterization), grouping/weighting of results, and data quality analysis (Pennington et al., 2004), all of which are then interpreted.

IV. Life Cycle Interpretation: At this step, the impact assessment results are provided, hotspots are identified, and where applicable, a comparison of the product systems with similar literature is provided. Further, a sensitivity analysis is conducted to determine the robustness of the results that required assumptions or where data gaps occurred and a data quality assessment is performed to identify data limitations (Matthews et al., 2014).

Additional analysis can include scenario or improvement analysis depending on the study's goal. Recommendations are made based on the defined goal and scope and on the limitations of the study (Rebitzer et al., 2004).

Chapter 2: Literature Review

Livestock production systems are a major contributor to global environmental impacts including the production of greenhouse gas emissions (GHG), the widespread degradation of land, biodiversity loss, and pollution of air and water, predominantly due to nutrient imbalances of N and P (Poore & Nemecek, 2018; Rojas-Downing et al., 2017; Potter et al., 2010; Ilea, 2009; Gerber et al., 2006; Daniel et al., 1998). The emissions from the global livestock industry are estimated to be 14.5% of total anthropogenetic GHG emissions production, equivalent to 8.1 gigatons of carbon dioxide equivalent (CO_2-eq) per annum (Gerber, 2013). In 2018, the total impact of livestock was estimated to contribute 3.5 billion tonnes of CO_2-eq (FAO, 2018). The Global Livestock Environmental Assessment Model (GLEAM), a Tier-2 LCA model that estimates the emissions associated with livestock and environment interactions such as emissions, converts the CO_2-eq using 100-year GWP based on the IPCC (2006) recommendations (298 kg CO_2-eq for N_2O and 34 kg CO_2-eq for methane (CH_4) and indicates that the livestock supply chain related GHG emissions consists of 50% CH_4, 24% N_2O, and 26% carbon dioxide (CO_2) (Cheng et al., 2022).

These impacts are increasing, considering the projected doubling of global demand for livestock products by 2050 due to population growth, economic expansion, shifts in dietary patterns, and urbanization (Thornton, 2010). According to the UN Food and Agriculture Organization (FAO) Agricultural Outlook 2021, the consumption of meat products is projected to grow by 14% by 2030, with poultry meat expected to represent 41% of all protein from meat sources (FAO. 2021). The study warns that shifting intensive livestock production in an environmentally sound manner is a critical global challenge (FAO, 2021).

In Canada, the agriculture sector is a major source of GHG emissions, with 73 Megatons of CO_2-eq (Mt CO_2-eq) produced in 2018, making up 10% of total domestic Canadian GHG emissions (Fouli et al., 2021). Canadian agricultural GHG emissions are emitted from various processes, with enteric fermentation, field crop and soil management, and manure management being the greatest emitters (Government of Canada, 2023). The emissions from energy use associated with production processes such as transportation and emissions from the production of nitrogen fertilizer are typically unaccounted for in agriculture (Qualman, 2022). By adding these GHG emissions to the agriculture industry, the estimated total GHG emissions for agriculture would be around 12% (Vergé et al., 2007). The poultry sector specifically contributes about 0.8 Mt CO_2-eq or about 1.0% of Canada's total annual GHG emissions (Qualman, 2022).

Manure, as a major by-product of the livestock industry, contributes considerably to the total estimated GHG emissions associated with the livestock industry, accounting for 25.9% due to the management practices (e.g., housing, handling, storage, treatment), field application, and direct deposit from grazing (Gerber, 2013). Nevertheless, the extent of these emission contributions varies due to the diversity in the livestock industry, including different animals, production systems, management strategies, climate conditions, and regulatory frameworks (Petersen et al., 2013). The environmental impacts associated with manure management practices depend on the type of animal, livestock concentration, management techniques, volume, nutrient composition, and environmental conditions (Petersen et al., 2013; Chadwick et al., 2011).

However, as livestock and poultry producers are typically concentrated in specific agricultural regions, by-products such as nutrient-rich manure accumulate and require intense management (Bryant et al., 2022). This accumulation of manure can be attributed to the intensification of agriculture throughout the last century (Bryant et al., 2022; Potter et al., 2010; Gerber et al., 2006). Vergé et al. (2009) state that "the industrial livestock industry has grown at twice the rate or more traditional mixed farms and at six times the rate of production based on grazing."

Historically, manure was recycled between crops and livestock within the boundaries of the farmstead. As the Green Revolution evolved and agriculture decoupled towards specialized commodity operations and livestock producers are now burdened with the accumulation of manure in concentrated regions (Bryant et al., 2022; Ramankutty et al., 2018; Schröder, 2005; Zhang & Schroder, 2014). This accumulation is a nutrient paradox as some agricultural regions experience nutrient depletion of N and P, while others are challenged with nutrient overload (Bryant et al., 2022; Lu & Tian, 2017; Potter et al., 2010). Today, livestock and poultry producers have limited opportunities to manage manure or sustainably recycle nutrients economically (Bryant et al., 2022).

2.1. Poultry Production and Manure Management

2.1.1. The Intensification of Poultry Production

Poultry and its secondary products are considered staple protein sources around the globe (Vaarst et al., 2015). The poultry industry is a significant part of Canada's food and agriculture sector, growing substantially from 101 million poultry birds (laying hens, broilers, and turkeys) to 154 million between 1990 and 2019 (Government of Canada, 2021). In 2020, poultry was estimated to be Canada’s most consumed animal protein and contributed an estimated $3.7 billion to the national economy (Government of Canada, 2021). In 2021, an estimated 1.34 million tonnes of broiler chickens and approximately 617.1 thousand tonnes of eggs were sold throughout Canada (Shahbandeh, 2022). Today, these numbers equate to approximately 2800 broiler farmers, 1000 egg and hatching farmers, and 551 turkey farmers who operate under the supply chain management system (Chicken Farmers of Canada, 2019).

With this growth, there is a priority to reduce production expenses and enhance output with more efficient operations. To meet these operational requirements, poultry operations, including broilers (for meat production) and layers (for egg production), typically encompass flocks numbering in the thousands to hundreds of thousands of birds. Production efficiencies have been facilitated by the transition to more intensive and specialized facilities, along with advancements in animal genetics, optimized nutrition, automation, and new production techniques (Pelletier et al., 2018). For example, many of today's producers utilize indoor open-floor systems or battery cages featuring automated feeding and watering systems (Mottet & Tempio, 2017). Driving factors responsible for the structural transformation in poultry farming mirror those impacting other livestock sectors: improved animal welfare, market demand, innovation, and economies of scale (Bryant et al., 2022).

2.1.2. Poultry Manure Production

Despite being relatively efficient feed converters and the operational advancements to the poultry industry, increased production has led to substantial volumes of waste (i.e., poultry excrement such as manure and urine) ((Bryant et al., 2022; Vaarst et al., 2015; de Vries & de Boer, 2010). These wastes are commonly summarized as manure and litter. Litter is a substantial waste stream within the poultry broiler sector for meat production (hereafter broilers). The use of bedding material contributes to the characterization of the poultry waste. Broiler litter consists of bedding material (e.g., woodchips, shavings, sawdust, and/or straw), manure, urine, excess feed, and water, as well as feathers and dead skin, resulting in a solid waste that is approximately 20-25% moisture content (MC) (Moore et al., 1995). Waste from laying hens for egg production (hereafter layers) typically consists of only excrement without any added bedding and is typically 70% MC (Moore et al., 1995).

Manure production and volume can vary greatly depending on poultry genetics and management strategies. For example, layers are estimated to produce approximately 64 to 94 g of manure per hen per day (Rahman et al., 2012). Based on the dry matter digestibility of the diet (87.5%), it is estimated that 0.34 – 0.63 kg of solids is excreted by a 35–49-day old bird per day or 43 kg/1000 kg live weight (Bolan et al., 2010). Calculations vary due to variations in manure and litter production rates and reporting (e.g., calculations based on wet basis vs dry basis or per bird vs per flock size or based on feed intake). In 2019, the Canadian poultry industry generated an estimated 2.2 million tonnes of poultry litter and manure (Statistics Canada, 2021). This estimate aligns with Pelletier (2017), which reported that Canadian layers produce approximately 1.1 million tonnes of manure annually. Nationally, between 1981 and 2001, manure production by poultry increased by 22.4% (879,000 tonnes) (Hofmann & Beaulieu, 2001). Although the poultry industry has undergone significant modifications to enhance efficiency and reduce costs for producing ample quantities of safe and affordable protein, efficient manure management practices are critical to advancing the Canadian poultry industry.

2.1.3. Poultry Manure Management

Traditionally, the fate of poultry manure and litter has been recycled to fields as an organic amendment. Utilizing recycled organic wastes is an agronomic practice that addresses soil fertility and is an accepted waste management strategy (Sahin et al., 2014; Flavel & Murphy, 2006). Poultry litter and manure display high concentrations of organic N as well as P and K while possessing beneficial soil health-building characteristics and documented contributions to increase soil fertility (Delgado et al., 2011; Rees et al., 2011; Bolan et al., 2010; Moore et al., 1995).

As a traditional nutrient amendment, raw poultry manure has been recognized as a manure product for its N and P content. Raw poultry manure is generally considered the most valuable livestock manure for fertilizer purposes (Bryant et al., 2022; Bolan et al., 2010; Moore et al., 1995). It is assumed there is variability in the nutrient content depending on the type of manure and management practices (Bolan et al., 2010). The major plant nutrients in raw poultry manure include N, P, K, Calcium (Ca), magnesium (Mg), and sulphur (S) (Bolan et al., 2010). Layer manure typically has a similar N content to broiler litter but with higher MC and concentrations of P, Ca, Mg, and Zinc (Zn) (Moore et al., 1995).

Today, the common practice of applying manure to fields may occur directly or after a subsequent storage period or treatment. Within Canada, farmers must adhere to manure management regulations that reduce nutrient losses, odours, and potential pathogens (Government of Nova Scotia, 2006). Farmers typically require temporary storage because of these regulations and the seasonality of manure spreading. This is especially true for confined livestock such as laying hens or broilers. A standard sequence of manure management includes collecting, storing, and possibly treating until producers can field apply to mitigate environmental losses while optimizing nutrient use efficiency (NUE) (Chadwick et al., 2011). Manure is typically applied through a spreader or injection system, sometimes surface applied or incorporated into the soil.

Poultry species, bedding, housing systems, volume, management styles, and economic costs determine manure storage and treatment methods. A common primary characteristic of manure that determines management is its MC. Manure is categorized as liquid (95% MC), semi-solid ("slurry") (84-95% MC), or solid (<84% MC) (Government of Nova Scotia, 2006). Various manure-handling practices and on-farm storage facilities exist in poultry production facilities due to the different production systems (e.g., floor, caged). Hen manure (liquid or slurry manure) is commonly stored in aboveground storage, such as tanks, or inground storage, such as anaerobic pits or lagoons (Bryant et al., 2022). In broiler production, which contains high amounts of bedding and is typically considered solid manure, litter collects on the floor during the production cycle and is then scrapped and hauled to a covered or uncovered stockpile (Bryant et al., 2022).

On-farm storage facilities are designed to prevent runoff and reduce odours depending on the manure type. Solid manure methods, including stacking, composting, or stockpiling, offer advantages such as lower initial infrastructure costs, potential for composting, and reduced nutrient runoff but are constrained by space requirements, odour, and handling challenges. A common storage system is roofed or open solid manure storage with a runoff storage facility (Government of Nova Scotia, 2002). Conversely, liquid poultry manure storage methods, such as lagoons, pits, or tanks, effectively reduce odours and facilitate field application through irrigation systems.

However, they require increased infrastructure and equipment costs and may require more management (Bryant et al., 2022).

In summary, the choices for solid and liquid poultry manure storage depend on the poultry operation (broiler or layer), manure characteristics, quantity, regulations, available land mass, resources, infrastructure, and equipment, with each approach having its distinct set of advantages and disadvantages.

2.1.4 Characterizing Dehydrated Poultry Manure

An alternative approach to reducing volume, odour, and storage requirements is drying and pelletizing poultry manure and litter. Dehydrated poultry manure offers practical benefits, including reduced cost to transport due to low water content, enhanced field precision during application, easier handling and storage, and pathogen elimination through pasteurization (Brunerova et al., 2020; Ronga et al., 2020; Sharara et al., 2018; Foged et al., 2011; Sultana et al., 2010). Typically, producing DPM involves drying with an energy source and pelletizing equipment like a wood pelletizer. This mechanical process employs chemical bonding, compression, extrusion, or tumbling to ensure the uniform formation of pellets, often comprising a mixture of multiple ingredients (e.g., supplemental nutrients or multiple feedstocks) (Sharara et al., 2021; Brunerova et al., 2020; Foged et al., 2011).

Reducing the MC is a critical process and purpose in pelleting manure. The moisture content of finished pellets is important as it can influence product quality and density (Brunerova et al., 2020). Literature indicates that drying and pelletizing reduces poultry manure that typically has over 60% MC to an average of 10.1% MC and assists in the physical properties of finished pellets (Brunerova et al., 2020; Ló Pez-Mosquera et al., 2008). Additionally, dewatering manure increases efficiency in transporting and distributing organic fertilizers (Ronga et al., 2020). Before dewatering, manure can contain high MC and high volume per tonne and requires large amounts of storage (Ronga et al., 2020). Dehydration and pelletization of manure for the purpose of fertilizer offer an economical way to transport valuable nutrients to producers.

The nutrient content of DPM is the primary reason for organic producers' interest in the fertilizer product. The drying and pelletizing impacts on the broiler litter create a more consistent product, especially regarding N form contents, P content and pH. (Ló Pez-Mosquera et al., 2008). Dehydrated poultry manure products in Eastern Canada typically range from 3-5% N, 1-3% P_2O_5, and 1-2% K_2O. As mentioned, DPM is sold and used in various production systems for home gardening, market gardening, and organic field crops. Research with various rates of DPM as an N amendment in organic production for wheat and potatoes in Eastern Canada has shown positive results on soil N, biomass, yield, and quality (Alam et al., 2018; Lynch et al., 2008; Sharifi et al., 2009). As DPM is an accepted fertilizer under Canadian organic standards, its agronomic benefits are particularly attractive to organic producers who find themselves limited in acceptable fertilizers.

2.2. Environmental Impacts of Poultry Production and Manure Management

2.2.1. Environmental Impacts of Poultry Production

Life cycle assessment (LCA) methodology has been widely used to characterize and quantify the environmental impacts of agricultural systems and products. The methodology provides a system approach to quantifying the environmental impacts of a product or process during its life cycle, identifying hotspots (high-impact life cycle stages), and comparing products or processes to ultimately assist in mitigating emissions (Pelletier et al., 2015). Extensive LCA research has been conducted in both the broiler and egg production industry on national and regional scales (e.g., Turner et al., 2022; Costantini et al., 2021; Pelletier et al., 2017; Putman et al., 2017; Leinonen & Kyriazakis, 2016; Boggia et al., 2010; Pelletier, 2008). On a global view, Costantini et al. (2021) reviewed poultry production systems that consider different sections of the supply chain (e.g., cradle-to-farm gate), different production methods, and management systems (e.g., organic, conventional, cage-free). Overall, it has been found with the intensification of poultry production, the environmental impacts of production per functional unit have decreased over the last 50 years (Turner et al., 2022; Pelletier et al., 2018; Putman et al., 2017; Pelletier et al., 2014).

The majority of impacts, including GWP, AP, and EP, associated with poultry and related products occur from the production of feed grain (i.e., crop production) due to the manufacturing and use of inorganic fertilizer inputs as well as the manure management stage (Turner et al., 2022; Costantini et al., 2021; Pelletier et al., 2017; Leinonen & Kyriazakis, 2016; Pelletier, 2008). Impacts related to feed grain production are due to fossil fuel and energy used to manufacture inorganic N fertilizer, as well as the leaching that occurs from nutrient loss and gaseous emissions such as N_2O from N fertilizer application (Leinonen & Kyriazakis, 2016; Pelletier, 2017).

Various LCAs have been conducted to evaluate the environmental impacts of poultry production systems, highlighting common factors influencing these impacts. Pelletier (2008) and Boggia et al. (2010) both emphasized the significant contribution of feed production to environmental impact categories, such as cumulative energy demand

(CED), GWP, AP, and EP, in broiler meat production. Similarly, Pelletier et al. (2014), Putman et al. (2017), and Pelletier et al. (2018) performed retrospective LCAs on the US egg and poultry industry, respectively, and identified feed-related processes, feed efficiency, and manure management as major contributors to environmental impacts. Notably, Putman et al. (2017) observed a decrease in climate change, AP, and EP per 1000 kg of poultry meat, attributed to improved fowl performance and background systems, despite an overall increase in environmental impacts per kilogram of poultry meat due to increased production. Pelletier et al. (2018) found the same patterns in U.S. and Canadian egg production over 50 years.

A comprehensive review by Costantini et al. (2021) covering 47 peer-reviewed LCAs across global poultry systems further affirmed the prominence of feed production and manure management in influencing environmental impacts. The studies commonly utilized impact categories such as CEU, GWP, AP, and EP. Importantly, many LCAs incorporated manure as an organic fertilizer, considering its role in avoiding inorganic fertilizer use and contributing to environmental benefits. These findings underscore the pivotal role of feed-related processes and manure management in shaping the environmental impacts associated with poultry production systems.

Turner et al. (2022) performed an updated cradle-to-farm gate LCA of the different housing systems (e.g., conventional, enriched, free run, and organic) in the Canadian egg industry with 2019 data based on the original literature from Pelletier (2017), which estimated the impacts of Canadian egg production housing systems for 2012 data. Results were reported based on one tonne of eggs in each housing system. Turner et al. (2022) reported that GWP and AP were lower for each housing system than

Pelletier's (2017) reported results. Feed per tonne of eggs (i.e., the amount of feed required for hens) was lower than Pelletier's (2017) analysis, apart from free range and organic housing systems. Although feed per tonne of eggs was higher for the free range and organic egg production, emissions decreased partially due to lower GHG emissions associated with upstream impacts or organic feed production than non-organic feed. Overall, EP emissions reported by Turner et al. (2022) were higher for each housing system due to the differences in manure management practices reported by Pelletier (2017). Overall, feed inputs and manure management were found to contribute the most to the selected impact categories. Turner et al. (2022) results align with a stand-alone LCA performed by Pelletier (2014), who also reported manure management to be the largest contributor to AP (45%) and EP (46%) and a significant contributor to the overall emissions associated with Canadian egg production.

2.2.2. GHG Emissions Associated with Manure Storage

Greenhouse gas emissions associated with manure are biogenic and determined by the manure composition; therefore, emissions can be somewhat controlled through management practices during handling, treatment, storage, and environmental conditions (Petersen et al., 2013). However, all stages of manure management contribute to GHG emissions. As Petersen et al. (2013) summarized, CH_4 emissions occur mainly from liquid or compacted manure by the anaerobic breakdown of organic matter through methanogenesis. The N_2O emissions occur via nitrification and denitrification during handling, storage, and after field application. Poultry manure is stored as solid waste, the aerobic conditions lead to a small amount of CH_4, whereas in poultry manure stored as liquid or slurry form the anaerobic fermentation can lead to higher amounts of CH_4 (Vergé et al., 2009).

2.2.3. Environmental Impacts Associated with Manure Applications

Excessive manure application, which surpasses the nutrient requirements of crops, has been linked to elevated nutrient levels of N and P, causing loss of nutrients through leaching, runoff, and erosion, thereby posing a substantial threat to pollution concerns (Kumar et al., 2013). Overapplication of nutrients, particularly NO_3 and phosphate (PO_3), contributes to losses in surface and groundwater runoff, leading to potential contamination of aquatic systems, jeopardizing drinking water, and increasing the risk of eutrophication (Petersen et al., 2007; Daniel et al., 1998). The severity of nutrient losses resulting from manure application is typically a response to climatic conditions, soil, and management techniques. Long-term application of poultry litter has been associated with the accumulation of NO_3 in the soil to a depth of 3 m (Kingery et al., 1993). In summary, most environmental problems associated with improper land application practices of manure by-products have centred on ground and/or surface water contamination with N and P.

Furthermore, manure applications to land are associated with emissions including CO_2, N_2O, CH_4, and NH_3 (Gržinić et al., 2023; Seidavi et al., 2019; Wang et al., 2019; Petersen et al., 2013). Although emissions vary depending on the air temperature, season, type of manure applied, and management practices, the surface application is a major contributor to NH_3 and N_2O losses from hen manure, accounting for most of the N losses in the manure management chain (Rosa et al., 2022). Overall, it is estimated that 92% of nutrients in manure are being returned to fields with little or no processing, typically due to insufficient manure storage capacities (Foged et al., 2011).

2.2.4. Resource Recovery Methods for Managing Poultry Manure

This robust reporting of the environmental impacts of manure management is an important factor contributing to the overall environmental performance of poultry production. It signifies the need for technological options to recycle manure into a value-added resource with a lower environmental impact. While many studies investigate the improvement of the poultry supply chain by exploring feed management (Van Asselt et al., 2015; Pelletier et al., 2018; Zhao et al., 2015), manure management (Rosa et al., 2022), and increase in NUE along supply chain of egg production (see Ershadi et al., 2023), the environmental performance of the conversion of poultry manure and litter into a dehydrated fertilizer pellet has had very little attention.

2.3. Waste Valorization and its Connection to the Circular Economy

With increased awareness of the environmental and social harms of primary resource extraction, government and industry are being pushed to move from a linear economy to a circular economy (e.g., a closed-loop product life). The Ellen MacArthur Foundation (2013) defines the circular economy (CE) as a system approach to treating waste and by-products as a secondary resource. Canada has committed to the United Nations Sustainable Development Goals (SDG), which has adopted the CE as an action plan (UN SDG, Goal 12, 2018). In agriculture, wastes and by-products can be transformed into economically valuable products such as energy, feed, and fertilizer through valorization processes (Hollas et al., 2022). The conversion of agricultural by-products is an example of the CE as it is critical to promote the utilization of waste and divert it from landfills, sustaining the bioeconomy, and shifting away from dependence on non-renewable resources while contributing economically. (see Duque-Acevedo et al., 2020). The literature surrounding the current obstacles of the CE with converting surplus manure into biogas and fertilizer has revealed it is not a straightforward venture with its technological, logistical, and social challenges (Akerman et al., 2020; Kapoor et al., 2020). However, Hollas et al. (2022) reviewed the CE strategies of various waste valorization strategies for livestock manure in terms of biogas, nutrient recovery, and water reuse. They found that manure treatments, such as anaerobic digestion, can assist in reducing greenhouse gas emissions within the agricultural sector as outputs can offset extractive fossil fuel use.

The growth in livestock intensification and the concentration of farming systems have been the driving forces behind the development and adoption of manure treatment technologies (Sommer, 2013). Increased demand for industrial fertilizer, energy and material has opened doors for industry to valorize livestock manure into a valuable resource that may substitute for primary resources (Hidalgo & Corona, 2023). Kabongo (2013) refers to waste valorization as industrial processing activities that involve the reuse, recycling, or composting of by-products to useful products or energy sources. It includes processing residues or by-products into valuable, usable products that may otherwise be lost to landfills (Kabongo, 2013). There is awareness that the valorization of poultry wastes (i.e., manure, spent hens, discarded eggs) is an increasingly important field of research that has grown since 2007 and is an important field of research due to the projected demand for poultry products and the options for poultry waste treatments (Kanani et al., 2020). Estimating the environmental impacts of valorized manure products and their production systems assists in understanding their role in the CE as a recycled product.

2.3.1. Valorization of Poultry Manure

There are several advanced methods of converting livestock waste into a valorized product due to the sheer volume of by-products and challenges with waste management. According to the FAO's report on "Tackling Climate Change through Livestock – A Global Assessment of Emissions of Mitigation Opportunities," there is a high possibility of reducing emissions by implementing manure management techniques that ensure nutrient and energy recovery and recycling from manure (Gerber, 2013). Currently, it is estimated that 13% of the waste management/waste valorization literature in Science Direct is livestock-specific (Kanani et al., 2020). Of the reviewed livestock-related literature (472 peer-reviewed publications), 63% focused on cattle and swine, while 22% focused on poultry waste (Kanani et al., 2020).

For poultry waste (manure, litter, discarded eggs, spent hens), the five main waste valorization technologies include co-digestion (anaerobic digestion), mono-anaerobic digestion, pyrolysis, and gasification (Kanani et al., 2020). These technology processes can yield fuel (biogas for heat and electricity) and biofertilizer while providing economic opportunity to producers, waste management companies, or entrepreneurs. Anaerobic digestion is a decomposition process without oxygen, allowing anaerobic bacteria to degrade organic matter, producing biogas (fuel for electricity) and fertilizer (Dornelas et al., 2016). Mono-anaerobic digestion uses one feedstock (Karki et al., 2021). Gasification of biomass converts feedstocks into gaseous fuel using heat, steam, and oxygen without combustion (Dept. of Energy, n.d.). Lastly, pyrolysis decomposes biomass at high temperatures, which can result in biofuel or biochar (Zhu et al., 2018). Various studies have examined the possibility of utilizing poultry manure for biofuels instead of direct field applications (Rubežius et al., 2020; Wang et al., 2019; Dornelas et al., 2016; Babaee et al., 2013).

2.3.2. LCA in Poultry manure Valorization

To understand the environmental impacts associated with manure management in poultry systems, LCAs have been widely used to estimate the environmental impacts of the valorization of manure and its relative performance as an input to various products and services. It is challenging to compare studies of manure valorization approaches as they have different goals, treatment methods, system boundaries, allocation approaches, and functional units. However, these studies estimated do provide the impacts of the manufacturing process required to valorize poultry manure into a secondary product system (biogas) using similar environmental impact categories such as CED, GWP, AP, and EP (Rubežius et al., 2020; Wang et al., 2019; Babaee et al., 2013).

Williams et al. (2016) performed a consequential LCA in which turkey litter, which has a similar guaranteed analysis as broiler litter, is a feedstock for a biogas system in the UK rather than directly applied to the field (displacing inorganic fertilizer). Based on a functional unit of 1000 kg of live-weight turkey, they determined that impacts associated with utilizing turkey litter for a biogas system were lower than if using the turkey litter as an amendment, significantly reducing AP (70%) and EP (55%) due to the avoided ammonia emissions from conventional manure management practices such as storage and land application.

Mainali et al. (2017) assessed the environmental impacts of treating poultry litter from rural layer operations in Bangladesh, comparing its use as biogas as a bio-fertilizer. This study was based on a functional unit of 10,000 eggs and revealed that the GWP of the layer operation could be reduced by 65% if poultry litter is used as a feedstock for anaerobic digestion to produce biogas and could reduce GWP by 17 times if 100% of the digested slurry was used as a bio-fertilizer.

Kanani et al. (2020) used a life cycle assessment to understand if poultry waste valorization technologies may improve environmental burdens compared to current manure management. Here, the researchers performed a comparative review of 105 LCA studies of different poultry waste valorization and found that anaerobic digestion, anaerobic mono-digestion, pyrolysis, and gasification were all suitable technologies to assist with increasing the sustainability of manure management in the poultry supply chain (Kanani et al., 2020).

In a review of 15 LCAs of biogas operations in the EU, Hijazi et al. (2016) found that biogas production has lower GHG emissions than conventional waste management practices. However, the overall environmental impacts of the biogas system were dependent on the feedstock type. Although manure waste from layer barns had the highest AP and EP compared to current manure management practices, AD reduces CH_4 and N_2O emissions.

A study which appears most similar to our study in question is Kiss et al. (2021), where researchers assessed the environmental impacts of producing composted pelletized poultry litter (CPPL) compared to various inorganic fertilizer blends (IFB). The CPPL product comprises broiler litter, layer manure, and by-products from slaughterhouse and pullet operations. It was found that the production of CPPL has a lower emission intensity than the selected IFBs per kg of product. When the production of CPPL and IFB was compared per 1 kg of active nutrients, CPPL had a higher environmental impact than individual chemical fertilizers due to the lower nutrient content.

Overall, a wide variety of literature estimates the environmental impacts associated with treating poultry manure. Most of the LCAs reviewed conclude that there is a decrease in emissions when poultry manure or litter is anaerobically digested compared to conventional manure management practices (direct to the field). LCAs of poultry manure treatment allow industry and researchers to further understand these wastes as value-added products with a potential contribution to the circular economy. However, when Sarlaki et al. (2021) summarize studies looking at the agronomic benefit of composted manure pellets, they do not note any literature detailing the environmental impact of the production or use. There appears to be little to no literature surrounding the estimation or characterization of environmental impacts associated with DPM.

2.3.3. Methodological Challenges in LCA of Manure Valorization

As life cycle assessment requires analysis and/or comparison based on the primary function of the product system, special consideration is needed when dealing with multifunctional systems where more than one product is produced (Michiels et al., 2021). In agricultural LCAs, specifically livestock product evaluations, more than one product is generally produced, resulting in multifunctional systems. For example, in poultry production, the main function is to produce meat or eggs from broilers and layers, respectively, as primary products, but there are then also potentially useful secondary or by-products, such as spent hens or manure (Pelletier et al., 2018). Within LCA, these are referred to as co-products if they are in a final state for use or as resource flows if they are further processed into secondary systems (e.g., manure applied to the field for nutrients). This creates a methodological decision regarding how to appropriately divide the inputs and environmental burdens amongst the primary product and co-products, and it is commonly known as co-product treatment or allocation according to ISO standards (ISO 14044, 2006).

To handle these methodological decisions, the ISO 14044 standards provide a hierarchy of preferred strategies to treat co-products in multifunctional systems (Pelletier et al., 2015). The first recommendation to fulfill the ISO standards is to avoid allocation (ISO 14044, 2006). Allocation refers to the "partitioning of the input or output flows of a process or a product system between the product system under study and one or more other product systems" (ISO 14044, 2006). The preferred way to assign environmental impacts to the co-products is to avoid allocation of impacts by:

I. Dividing the aggregated process that produces the multiple products into unit processes and collecting data separately for each process allows processes to share environmental burdens amongst products by dividing the unit processes into two or more sub-processes. However, this is not practical or possible in many situations (Pelletier et al., 2015).

II. Using system expansion (avoided burdens approach), the boundary of the product system is expanded to include a product in which the co-product substitutes and the impacts associated with that product are subtracted. System expansion is only used for consequential LCA and not attributional LCA (Pelletier et al., 2015).

If allocation cannot be avoided, then the inputs and outputs of the system are divided among the different products based on a physical relationship (e.g., mass or nutrient content) preferably. If not feasible, the allocation is based on an economic relationship (ISO 14044, 2006). This allocation approach will complicate such decisions as the unit of measurement will influence the conditions of the analysis.

The general guidance in the LCA ISO standards is that co-products and resource flows should be dealt with according to the product system being studied, ensuring it best represents the physical reality and the system's function in the economy. Often, LCAs are conducted based on what has been previously published in the literature without consideration of the specific product or the context of the study (Pelletier and Tyedmers, 2011). For manure valorization LCA studies, there have been recent methodological contributions on how to deal with manure as a co-product or resource flow, which consider various contexts, providing a more nuanced approach (Michiels et al., 2021; Liep et al., 2019; Chen et al., 2017; Mackenzie et al., 2017; Pelletier et al., 2015). The primary methodological challenges and contextual factors appear to include: i) defining manure to its fate (e.g., waste, co-product, residual), ii) determining the multifunctional systems approach selected under the ISO standards (e.g., system expansion, allocation), iii) if using allocation, then deciding which allocation approach to use (e.g., economic, mass, biophysical). Within studies, livestock manure can be defined as a “residual” (i.e., provides an environmental credit as it displaces inorganic fertilizer), a “waste” (i.e., environmental burdens belong to the main system or at times hold no environmental impact), or “co-product” (i.e., is viewed as a valued product that holds some environmental impact). Multifunctional products in livestock systems are commonly not mentioned (Costantini et al., 2021).

How the manure is defined within the system will result in different environmental trade-offs throughout the LCA analysis, such as manure increasing contributions to environmental impact categories, decreasing the contributions as manure can be considered a substitute for inorganic fertilizer, or not contributing any impacts (Michiels et al., 2021; Leip et al., 2019; Hoffman et al., 2018; Leinonen & Kyriazakis, 2016). If manure is used as an organic nutrient amendment for crop production, it is defined as a 'residual.' It is thus regarded as either not having an environmental impact on the production system in the study or provides the system in question with a credit as the manure is sometimes assumed to replace the use of inorganic fertilizer (Constantini et al., 2021; Michiels et al., 2021; Hanserud et al., 2018; Meier et al., 2014; Boggia et al., 2010). When manure is considered a "waste" from livestock systems (i.e., it is not used as a nutrient amendment but is landfilled, used as a nutrient but is considered waste, or is applied more than crop nutrient requirements (Leip et al., 2019)), then the activities and impacts associated with handling the manure waste, including waste management, are associated with the main product, such as meat or hens (Hoffman et al., 2018). These approaches are especially problematic as they not only prescribe zero-burden associated with manure but also assume a credit as it substitutes the production, transportation, and application of inorganic fertilizer.

Defining manure as a co-product assists in addressing the environmental impacts associated with production and the overall impacts of a livestock system. Appropriately partitioning the environmental impacts of a livestock system is a critical step in recognizing the value of manure (Leip et al., 2019). However, allocation methods can greatly alter the environmental outcomes of products or systems being examined depending on whether the environmental impacts are partitioned through biophysical, mass, or economic allocation (Chen et al., 2017; Pelletier et al., 2015). Vergé et al. (2015) analyzed three separate allocation methods (no allocation, economic allocation, and mass allocation) for assessing the environmental impacts of the Canadian pork industry. They found a 6 and 46% difference between environmental impact results per kg of product.

Although economic allocation is the last recommended approach in the ISO standards (ISO 14044, 2006), it is a common methodological choice in poultry systems (Costantini et al., 2021). There is much contention with this approach as it does not accurately capture the complete environmental impacts of a production system (Hoffman et al., 2018). In economic allocation, the environmental impacts are quantified based on the economic value of input or output (Michiels et al., 2021). However, there are many concerns with this approach as it is challenging to select a price that reflects the value of each co-product and is sensitive to market fluctuations (Bier et al., 2012). In a review, Michiels et al. (2021) found that the impact of an output changes with its price while its manufacturing stays the same. Due to economic allocation dependence on market prices, the environmental outcomes are subject to change due to external market fluctuations, which could result in obsolete LCA data and create difficulties in comparing the results of LCA studies which used different market conditions (Michiels et al., 2021; Pelletier & Tyedmers, 2011).

In recent literature, manure is recommended to be recognized as a co-product and have environmental burdens allocated based on a biophysical relationship (Michiels et al., 2021; Leip et al., 2019; Hoffman et al., 2018; Chen et al., 2017). Leip et al. (2019) suggest that as manure is a valuable co-product, the inputs and environmental impacts are to be allocated using a biophysical approach based on the caloric energy to produce the manure. Providing an environmental burden to manure based on a physical or economic basis ensures accountability within the agricultural industry.

Turner et al. (2022), Pelletier (2017) and Putman et al. (2017) use a biophysical approach to account for the impacts between co-products that had economic value. For example, Turner et al. (2022) based the physical relationship of co-products on gross chemical energy content for both eggs and spent hens. The excretion of N and P was calculated based on a nutrient mass balance model using feed composition. The volume was based on an average excretion rate of layers based on relative feed conversion efficiencies to calculate the losses and assign impacts to the manure. Estimates of N and P were then used to calculate emissions and leachate (e.g., NH_3, N_2O, NO_3) under IPCC (2006) Tier-2 protocols. The biophysical approach was based on the multifunctional principles discussed in Pelletier and Tyedmers (2011) and Pelletier et al. (2015).

Michiels et al. (2021) analysis compared the environmental impact results of different methodological decisions considering manure as an organic fertilizer from a beef cattle system through a residual approach (no burden or credit), system expansion, and different economic and mass allocation factors. Although four of the mass allocation factors resulted in some unrealistic results (e.g., manure owning over 100% of the impacts because the weight of the manure outweighs the meat produced or the beef meat accounting for less than 13% of all impacts), it was concluded that a mass allocation approach (in their case; kg N in organic fertilizer/(kg live weight + kg N in manure)) was the preferred option for estimating the impacts associated with organic fertilizers because it provides the closest approximation that represents real-world scenarios accounting for an estimated in less than 16% of the impacts being allocated to organic fertilizers.

An additional approach is to consider manure as a "resource flow." As a resource flow, the manure is then recycled in a secondary system and added to other useful products. In this case, manure would not be treated as a co-product, and therefore, LCA recycling rules were applied to its use rather than allocation approaches. This 50/50 recycling approach has been used to determine impact partitioning in end-of-life scenarios such as recycling, reuse, incineration, and disposal (Allacker et al., 2014). Under the 50/50 recycling approach, 50% of the impacts associated with the original resource or product are counted in the subsequent product system (Allacker et al., 2014). The nutrient value of manure is considered to be a recycling of the nutrients from the inorganic fertilizer used to produce grain feed. Therefore, as the manure is recycled into a secondary system, the upstream impacts of manufacturing inorganic fertilizer are accounted for.

2.3.4. Assessing Methodological Approaches to Account for Upstream Impacts of Manure

Similar to livestock LCAs, there is a wide perception that the valorization of residuals, wastes, or co-products that may otherwise go to landfill (or field application), used in the additional system should be treated as burden-free (Michiels et al., 2021). However, this is a common misconception as all inputs in a product or process have an environmental "cost" (see Olofsson & Borjessin, 2018). Some studies analyzing the impacts of manufacturing value-added manure products for fertilizer do not recognize the upstream impacts of manure (see Kiss et al., 2021; Sarlaki et al., 2021; Bora et al., 2020). Another common approach is recognizing manure as an input when comparing the environmental impacts of manufacturing fertilizer. However, this provides credit to the system as it offsets the inputs associated with not using inorganic fertilizer (see Corbala-Robles et al., 2018; Williams et al., 2016). Accounting for using manure in a value-added system as a credit omits any upstream impacts associated with its use.

This appears to be a commonly discussed challenge in LCA, especially with the increased interest in the circular economy and the desire to assess the environmental impacts of valorized waste systems (Schrijvers et al., 2015). A recent review which assessed different allocation methods of 113 organic waste valorization LCAs found that with the attributional LCAs, the most common strategy was to avoid allocation by assuming zero-burdens associated with the utilization of waste (Dominguez Aldama et al., 2023). This literature showcases that many LCAs do not account for the upstream impacts of value-added resources and may lead to misguided decisions on low-impact, bio-based products (Olofsson & Borjessin, 2018).

2.4. Research Objectives and Core Ideas

It has become increasingly important to manage and distribute manure responsibly. With this challenge comes the opportunity to valorize manure and increase its circularity through treatments that produce value-added products such as an organic fertilizer. The dehydration and pelletizing of poultry manure is an example of manure valorization for use as an organic fertilizer in crop production. However, very few studies provide a comprehensive understanding of the environmental impacts of DPM manufacturing. To the best of our knowledge, the manufacturing process and the included inputs and impacts associated with the production of DPM have yet to be characterized or quantified through LCA.

2.4.1. Research Objectives

This research aims to estimate the life cycle environmental impacts associated with the manufacturing of DPM within Eastern Canada, from manure sourcing, manufacturing, and packaging, encompassing the entire "cradle-to-facility gate" process. This study incorporates product and manufacturing data collected in collaboration with two pelletizing industries to estimate the average environmental impacts throughout the DPM manufacturing life cycle.

The specific objectives of this project are to:

1. Estimate the environmental impacts associated with the manufacturing of DPM.
2. Identify processes or life cycle stages of DPM with high impacts (hotspots).

Chapter 3: Life Cycle Assessment Methods

3.1. Life Cycle Assessment Methodology

To estimate the environmental impacts associated with dehydrated poultry manure (DPM) in Eastern Canada, the ISO 14040-14044 (2006) four-phase methodological framework was followed. Specific details and technologies are not described to maintain the confidentiality of the manufacturing practices, production volume, and markets of the partnering companies. Instead, generic life cycle stages are identified, and the two companies' results are arithmetically averaged to estimate the environmental impacts of DPM production in general.

3.2. Goal and Scope Definition of the LCA of DPM Manufacturing in Eastern Canada

The study's overall goal is to evaluate the life cycle environmental impacts associated with manufacturing DPM and to determine hotspots of impacts for improvement analysis.

3.2.1. Product System Description

The manufacturing of DPM typically entails several stages involving the sourcing of poultry manure or litter (hereafter, the term manure will be used to encompass both manure and litter), followed by dehydration or drying, facilitated by an energy source. Subsequently, the dried material undergoes pelletization using a wood pelletizer, and the resulting pellets are stored in grain or fertilizer bins or packaged into totes or smaller units. Depending on the intended application, the pellets can be customized in terms of particle size. Finished pellets typically have two pathways. They can i) be conveyed to the packaging hopper or ii) transferred into the granulation tower, which results in a granule DPM product that then goes to the packaging hopper. Additionally, supplemental nutrient additives can be added while producing DPM to yield various DPM products with different GA and intended purposes. The final DPM products are distributed either in bulk or packaged forms, either to farm retailers or directly to farms

3.2.2. Functional Unit

A functional unit is a quantifiable unit that describes the function of a product or process (Weidema, 2006). The functional unit provides a reference basis for comparing and analyzing goods or services (Rebitzer et al., 2004). In the case of DPM, the ultimate function of the product is to provide nutrients for crop growth. However, since this LCA stops at the facility gate, an intermediate functional unit is used based on the function of the DPM facility, which is to produce DPM. Therefore, the functional unit is one metric tonne (1 tonne) of packaged DPM with an average MC of 8% and a guaranteed analysis of 4-2-1.

3.2.3. System Boundaries for Assessing the Manufacturing of DPM

The system boundary considers all activities associated with the manufacturing of DPM from cradle-to-facility gate (Figure 1). This includes all raw material extraction and processing (e.g., fossil fuel manufacturing, inorganic fertilizer manufacturing, electricity production, and manufacturing of packaging materials), manure sourcing, manure drying, DPM pelletizing, and DPM packaging. The impacts associated with poultry production (e.g., egg or broiler meat production) and field application are outside the system boundary (i.e., not included in this analysis) as this analysis focuses on the environmental impacts associated with manufacturing DPM. The distribution of DPM sold to agriculture retail and directly to farms is excluded from the analysis as the customer base and markets may fluctuate, altering the distance travelled and the volume of the DPM sold.

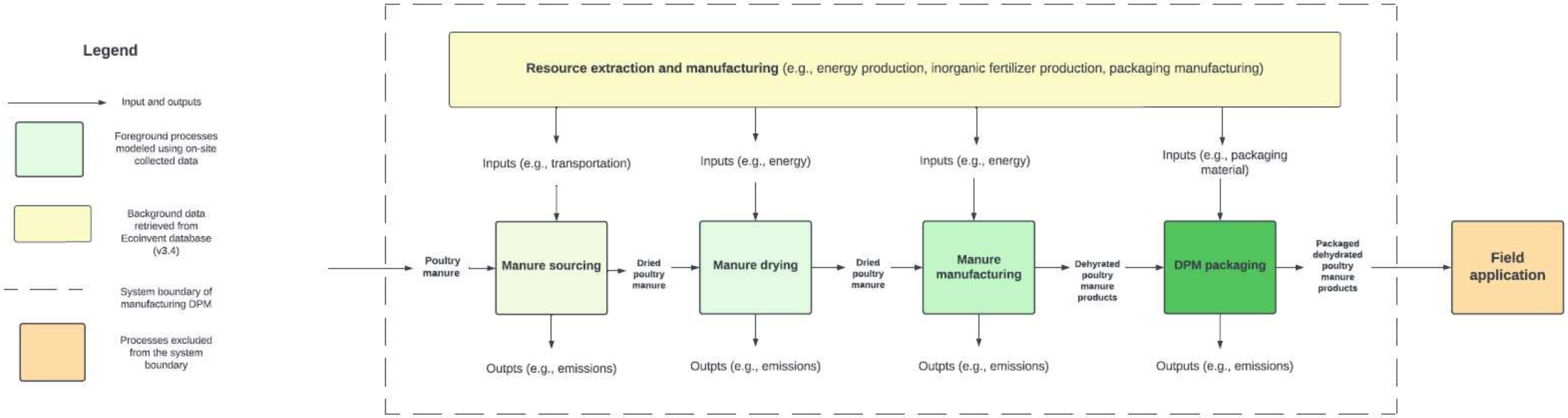

Figure 1: System boundary of manufacturing DPM in Eastern Canada.

3.2.4. Environmental Impact Categories

An impact category represents the environmental impacts of concern to which the life cycle inventory analysis results are assigned (ISO 14044, 2006). The environmental impact categories selected for evaluating the life cycle of DPM include:

Global warming potential (GWP) (kg CO_2-eq)

Terrestrial acidification potential (AP) (kg SO_2-eq)

Freshwater eutrophication potential (EP) (kg P- eq)

Respiratory effects (RE) (kg PM2.5-eq)

These four impact categories are selected due to their prevalence and relevance to the fertilizer supply chain and poultry manure. McClelland et al. (2018) reviewed 173 livestock LCA studies and identified that 98% included GWP, 50% included EP, and 54% included AP. Having multiple impact categories allows the representation of a more holistic view of DPM manufacturing impacts. Three midpoints and one endpoint category (RE) were selected. Midpoint categories recognize an environmental effect before damage occurs, such as GWP, AP, and EP, whereas endpoint categories recognize the final environmental damage that can occur. GHG emissions, NOx, and particulates were measured on-site at one facility, and emissions of CO_2, which is associated with GWP, particulate matter (PM), associated with RE, and carbon monoxide were identified. These emissions were included as input data.

The impact potentials were calculated using the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI v2.1) environmental impact method within the openLCA software (GreenDelta, Berlin, Germany, 2022).

3.3. Life Cycle Inventory (LCI)

The LCI phase involves accounting for all the inputs and outputs from each process in the product system. The data types required are the quantity of inputs (materials and energy used) and outputs (products, waste, and emissions) associated with each activity. A description of data collection, calculations and associated assumptions follows.

3.3.1. Life Cycle Inventory Data Sources

Life cycle inventory data were collected from two individual DPM manufacturing companies. Site tours of each facility were conducted in 2022 to understand the specific manufacturing details and technologies used by each company and to identify all the steps in DPM manufacturing. A questionnaire was sent to each company to collect data on their processes, annual estimates of inputs such as volume of manure, energy sources (e.g., electricity consumption, fossil fuel usage, annual energy bills), materials used (e.g., packaging), and any other additional inputs (e.g., cleaning agents, additional feedstocks, maintenance supplies), as well as relevant data on outputs such as total annual production, wastes, or knowledge of emissions from previous environmental assessments.

Once data was collected, the data from each company was compiled in Microsoft Excel. On-site processes were organized into four categories, including i) manure sourcing, ii) manure drying, iii) DPM manufacturing of pellets, and it) on-site DPM packaging. Inputs and outputs associated with each process (e.g., energy, equipment oils such as lubricants, packaging material, and product output) were identified. Data was verified, and follow-up video calls and emails from company representatives filled data gaps. Some data required further literature reviews, assumptions, and calculations, such as estimating the electricity usage of the manure drying systems and upstream impacts associated with the use and production of poultry manure, described in detail in the following section. The life cycle inventory data of the companies cannot be shown due to confidentiality agreements. Background data were sourced from the ecoinvent v3.4 LCI database. Electricity production was based on the ecoinvent v3.4 database and with the reflected provincial market provider.

3.3.2. Modeling the Manufacturing of DPM

The LCI data is organized by defining and understanding the product system and its processes, including the identification of the inputs and output flows related to each process. As data for individual processes was not separable in some cases, the data was aggregated into three processes: Manure sourcing, Manure drying, DPM manufacturing, and DPM packaging (Figure 1). This analysis is based on the total amount of inputs included in the annual production of each company's products; analyses and results are not separated across different product types with different nutrient analyses or packaging and are solely based on the functional unit of 1 tonne of DPM, packaged.

3.3.3. Characterizing Each Process Involved in Producing DPM

Manure is derived from conventionally raised poultry systems from barns located within Eastern Canada. The manure derived from the poultry systems primarily consists of feces, urine, traces of feathers, feed, and, in the case of broilers, bedding material such as straw or wood shavings.

Manure Sourcing: Manure is collected from the barn floors at the end of the production cycle (broilers) or continuously collected (layers) to be dried on-site or transported to another location to be dried. The manure is sourced from both broiler and layer barns. The sourcing of raw manure includes transportation from the barns to the pelletizing facility. The manure has an average guaranteed analysis (GA) of 4-2-1 NPK. Manure is a resource flow that recycles NPK into the DPM system, so this process includes the upstream impacts associated with poultry manure (inorganic fertilizer production).

The recycling approach was used to account for the impacts of manure production. Specifically, in the 50/50 approach, 50% of the environmental burden of producing the fertilizers represented as nutrients is assigned to the DPM. This applies only to the fraction of fertilizer nutrients contained in the manure (i.e., the GA of DPM of 4-1-2); the remainder of the fertilizer impacts are associated with the laying hen operations. It was unknown whether the GA was the same for the raw manure source as it was for the final product, and ideally, a nutrient analysis of the raw manure would be available. Nevertheless, it was assumed the GA was the same for the raw manure source as it assumed only moisture was lost during the processing and no nutrient loss. The input quantity for each nutrient was based on the functional unit of 1 tonne of DPM. For example, as DPM is 4% total N, there is an estimated 40 kg of N in 1 tonne. By applying the 50/50 recycling approach, 50% of the environmental impacts associated with manufacturing 40 kg of N, for example, would be assigned to 1 tonne of DPM. This was modelled by including 20 kg N fertilizer (i.e., 40 kg N * 50%) in the life cycle inventory per 1 tonne of finished DPM product. The same approach was applied to P as P_2O_5 and K as K_2O fertilizer inputs.

Manure Drying: The manure is dried from 30 - 85% MC to 5-10% using two different drying technologies (confidential). Energy demand for drying is dependent on the MC of the manure or litter.

DPM Manufacturing: The dried manure is augured into the pelletizer, where supplementary nutrients to adjust the GA may be added. Then, it is pelletized with a pelletizer similar to a wood pelletizer. Maintenance includes cleaning using company-specific protocols.

DPM Packaging: The pellets are packaged using various packaging materials, depending on the company and its markets. Once packaged individually, the pellets are put onto pallets or wrapped using plastic film. Table 1 describes the generic manufacturing processes and associated inputs involved in manufacturing DPM in Eastern Canada. As mentioned, the transportation of finished products is excluded from the analysis as customer base and market locations can change, and the study's goal was to understand the environmental impacts of producing the manure.

The LCI database ecoinvent (v3.4) (ecoinvent, Zürich, Switzerland, 2022) provided the LCIs with background data such as fertilizer manufacturing, energy production, and material production. The database Agribalyse v3.1 was used for specific inputs (e.g., additives, confidential) that were unavailable in ecoinvent v3.4.

Table 1:Modeling the life cycle inventory based on average inputs for each process included in manufacturing DPM.

Process: Manure Sourcing		
Input	**Unit**	**Source**
Inorganic N (total) (manure)	kg	Company data, calculations, Allacker et al. (2014)
Inorganic P (P_2O_5) (manure)	kg	Company data, calculations, Allacker et al. (2014)
Inorganic K (K_2O) manure)	kg	Company data, calculations, Allacker et al. (2014)
Sourcing of manure (transportation)	tonne*km	Company data, calculations
Output	**Unit**	**Source**
Raw manure	tonne	Calculated
Process: Manure Drying		
Input	**Unit**	**Source**
Raw manure	tonne	Calculated
Energy for drying	MJ or kWh	Company data, assumptions, calculations
Output	Unit	Source
Semi-dried manure	tonne	Calculated
Process: DPM Manufacturing		
Input	**Unit**	**Source**
Semi-dried manure	tonne	Calculated
Energy inputs	kWh, L, or m^3	Company data calculated
Supplemental nutrients	kg	Company data, calculation
Equipment cleaning	kg	Company data
General maintenance inputs	kg	Company data
Output	**Unit**	Source
DPM	tonne	Calculated
Process: DPM Packaging		
Input	**Unit**	**Source**
DPM	tonne	Calculated
Various packaging materials	kg	Company data, calculations
Output	**Unit**	**Source**
Packaged DPM	tonne	Calculated

3.3.4. Assumptions and Data Quality

3.3.4.1. Estimating the Energy Required in Manure Drying

Manure drying is a critical component in the production of DPM, as manure is required to be a certain MC to produce quality pellets. Additionally, as manure is the primary input to the DPM system, it was essential to appropriately estimate the energy required to dry manure for the two company-specific drying systems. In the case of both drying systems, assumptions were needed to estimate the energy required to dry the manure due to data gaps. Manure drying inputs were based on energy consumption per tonne of DPM.

3.3.4.2. Sensitivity Analyses

The sensitivity analysis aims to evaluate how changes to a model affect the baseline results. This portion of the analysis allows us to evaluate the robustness of selected inventory data, assumptions, and hotspots and examine how sensitive the results are to parameter or methodological changes. Sensitivity analysis may be applied to inputs such as inventory data, processes, or assumptions in the model, as well as methodological choices, such as allocation procedures, the functional unit, or an environmental impact method. When conducting a sensitivity analysis, only one variable is changed to determine how sensitive the results are to this parameter and if it affects the interpretation of the results. The following data and assumptions were involved in the activities with the highest impacts and required sensitivity analysis.

- Choice of provider for high-voltage electricity in ecoinvent database (market mix vs production mix for the province).
- Choice of provider for inorganic N fertilizer data in ecoinvent database (Canadian market mix vs Global market mix).

- Characterization factor for CO_2 emissions associated with estimating the upstream GWP impacts of using residual wood biomass as a biofuel.
- Adjusting the estimated power rating of the fans on the manure dryer (25, 50, and 75% capacity)
- Adjusting the 50/50 recycling approach to account for the upstream emissions associated with the use of poultry manure (NPK fertilizer) to 100% and 0%.

Table 2: Sensitivity analyses performed on the baseline results of manufacturing 1 tonne of DPM in Eastern Canada.

Input parameter	Baseline selection	Sensitivity analysis
High-voltage provider	Provincial production mix	Provincial market mix
Inorganic N fertilizer provider	Canadian market mix	Global market mix
GWP characterization factor for the CO_2 emissions of the combustion of RWB	GWP characterization factor of 1.0	GWP characterization factor of 0.5
Adjusting the power rating of the fans on the manure dryer that run 24/7	Fans are assumed to run at 100% capacity	Reducing the power rating by 25, 50, and 75% capacity
50/50 recycling rule applied to the upstream impacts associated with poultry manure	50% of upstream impacts associated with litter are sourced from inorganic NPK fertilizer	0% and 100% of upstream impacts associated with litter are sourced from inorganic NPK fertilizer

Chapter 4: Results and Discussion

4.1. Introduction to Results

This chapter presents the LCA results of the environmental impacts associated with the manufacturing of DPM. The primary goals were to quantify the overall environmental impacts using a cradle-to-facility gate boundary and to identify hotspots. Overall, this analysis will provide insights into potential areas for reducing the environmental impacts of DPM pellet production. Due to confidentiality agreements, company-specific input data and individual company environmental impact results cannot be shared; therefore, results represent the arithmetic average of the two technologies used to produce 1 tonne of DPM packaged pellets.

4.2. Environmental Impact of Manufacturing DPM Pellets

The average total environmental impacts per 1 tonne of packaged DPM are GWP: 299.2 kg CO_2-eq; AP: 1.3 kg SO_2-eq; EP: 0.7 kg N-eq; RE: 0.2 kg PM2.5-eq. Manure sourcing was the largest hotspot (49% of the GWP), contributing 146.7 kg CO_2-eq to GWP, 0.8 kg SO_2-eq to AP, 0.4 kg N-eq to EP, and 0.1 kg PM2.5-eq to RE based on 1 tonne DPM pellets (Table 3). This was due to the environmental burdens associated with the manure's NPK content (4-2-1). This NPK arises from the inorganic fertilizer used to produce the feed for the poultry production, part of which ends up in the manure. The environmental burdens represent the upstream impacts of fertilizer production. The impacts associated with inorganic N fertilizer represent the greatest share of the burdens of manure sourcing (95.0 kg CO_2-eq for GWP, or 39% (Figure 2)).

Table 3: Estimated environmental impacts of manure sourcing and associated inputs presented as an average per 1 tonne of product for two manufacturers in Eastern Canada.

Manure Sourcing						
Input		**GWP (kg CO_2-eq)**	**AP (kg SO_2-eq)**	**EP (kg N-eq)**	**RE (kg PM2.5-eq)**
Inorganic NPK fertilizer (in manure)	N	95.0	0.5	0.3	0.1
	P_2O_5	25.7	0.1	0.1	0.0
	K_2O	7.9	0.0	0.0	0.0
Transportation of manure		18.2	0.1	0.0	0.0
Total to Manure Sourcing		146.7	0.7	0.4	0.1

Manure drying contributed greatly to GWP with 89.6 kg of CO_2-eq (30% of the GWP) and modestly to AP, EP, and RE (Table 4), mostly due to the upstream impacts associated with energy production and use, such as electricity and the combustion of biofuel. DPM manufacturing contributed moderately across all impact categories (16% of GWP), with 47.2 kg CO_2-eq to GWP, 0.3 kg SO_2-eq to AP, 0.3 kg N-eq to EP, and 0.1 kg PM2.5-eq to RE (Table 5). Lastly, Pellet packaging consistently contributed the least across all environmental impact categories (5% of GWP) (Table 6).

Table 4: Estimated environmental impacts of manure drying presented as an average per 1 tonne of product for two manufacturers in Eastern Canada.

Manure Drying				
Input	**GWP (kg CO_2-eq)**	**AP (kg SO_2-eq)**	**EP (kg N-eq)**	**RE (kg PM2.5-eq)**
Energy	89.6	0.1	0.0	0.0
Total to Manure Drying	89.6	0.1	0.0	0.0

Table 5: Estimated environmental impacts of DPM manufacturing and associated inputs presented as an average per 1 tonne of product for two manufacturers in Canada.

DPM Manufacturing				
Input	**GWP (kg CO_2-eq)**	**AP (kg SO_2-eq)**	**EP (kg N-eq)**	**RE (kg PM2.5-eq)**
Energy	39.9	0.2	0.2	0.1
Supplemental nutrients	4.6	0.1	0.0	0.0
Equipment maintenance	0.1	0.0	0.0	0.0
Equipment cleaning	2.7	0.0	0.0	0.0
Total to DPM Manufacturing	47.3	0.3	0.2	0.1

Table 6: Estimated environmental impacts of DPM packaging presented as an average per 1 tonne of product for two manufacturers in Eastern Canada.

DPM Packaging				
Input	**GWP (kg CO_2-eq)**	**AP (kg SO_2-eq)**	**EP (kg N-eq)**	**RE (kg PM2.5-eq)**
Packaging material	15.6	0.1	0.1	0.0
Total to Packaging Material	15.6	0.1	0.1	0.0

Figure 2 describes the average environmental contributions of the grouped inputs of the two DPMs. Within the Manure sourcing process, the major contributing inputs are the inorganic N, P, and K (poultry manure) derived from manufacturing inorganic fertilizers for feed production, with the production of inorganic N consistently contributing the most across all environmental impact categories assessed. The combined GWP impact of the three nutrient sources in the manure accounted for an average of 128.6 kg CO_2-eq per tonne of DPM. The contributions of nutrients in the manure toward AP, EP, and RE are 0.6 kg SO_2-eq, 0.4 kg N-eq, and 0.1 kg PM2.5-eq per 1 tonne of packaged DPM, respectively, with inorganic N fertilizer being the primary contributor. The transportation involved in sourcing the raw poultry manure is estimated to contribute 3-7% across all impact categories. Energy inputs used for manure drying accounted for 30% of GWP impact and 10% of AP, but only modestly to EP and RE. Within the DPM manufacturing process, the energy inputs required to operate the facilities and manufacture DPM accounted for between 13 and 39% of impacts across environmental categories. Additional inputs such as supplemental nutrients, maintenance, and cleaning had relatively minor contributions to the impact categories. DPM packaging contributed from 5% to 8% across impacts.

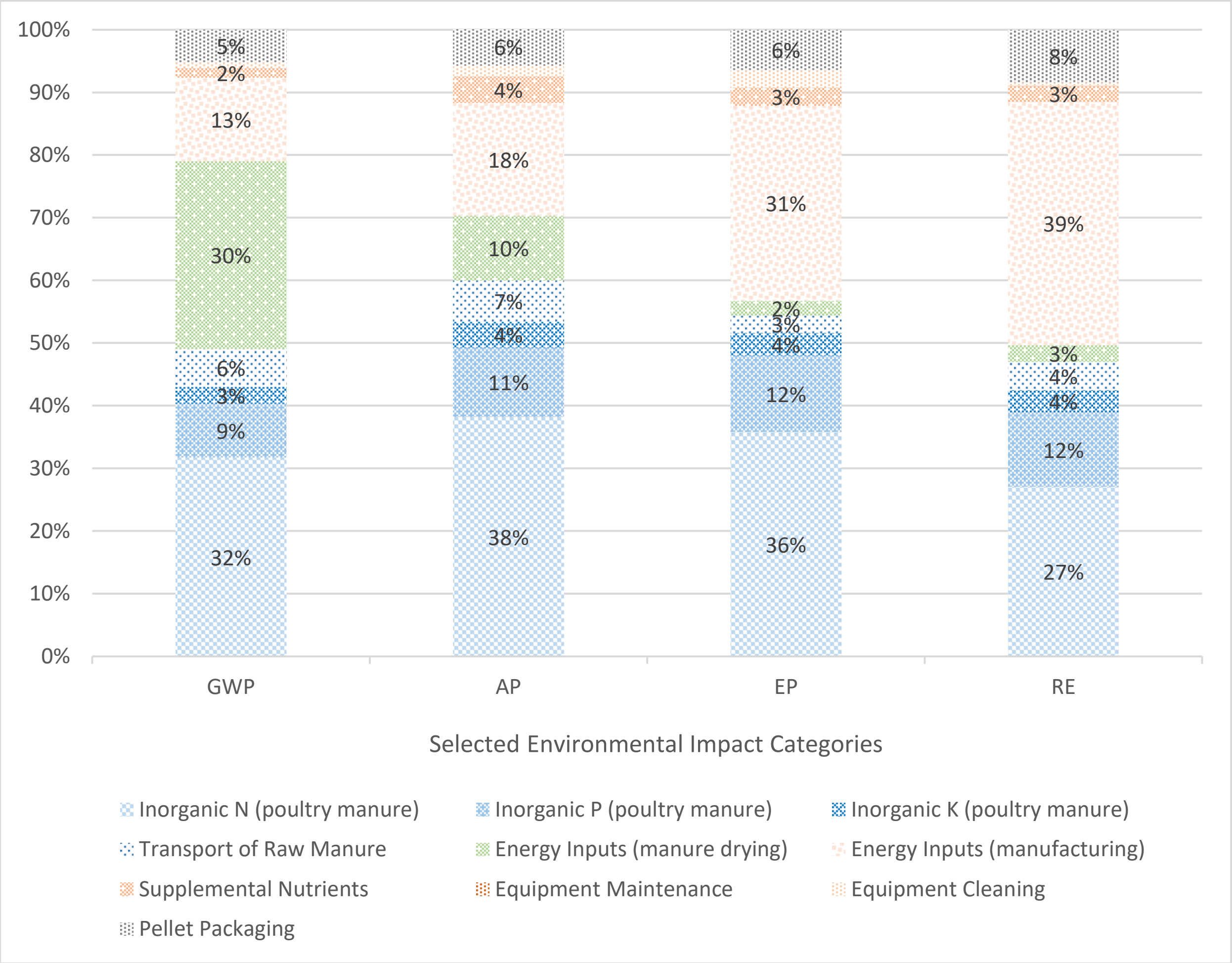

Figure 2: Percent contribution of inputs to DPM manufacturing processes to selected environmental impact categories (GWP – global warming potential; AP – acidification potential; EP – eutrophication potential; RE – respiratory effects) based on 1 tonne of packaged DPM in Eastern Canada.

4.3. Sensitivity Analyses

In LCA studies, sensitivity analyses are conducted on uncertain data, assumptions, and methodological decisions, particularly when these issues are associated with hotspots.

For the use of RWB as a biofuel, the baseline model used a GWP characterization factor of 1.0 for C emissions from RWB combustion, meaning that the CO_2 emitted from the combustion of RWB will have GWP impacts like fossil fuel carbon (i.e., it assumes that all the carbon in the forest biomass is not recaptured through forest regrowth). This characterization factor is conservative as it represents the worst-case scenario for Eastern Canada in a forest management system and the highest potential impacts associated with the combustion of forested bioenergy. It was chosen because no information was available on managing the forest. A sensitivity analysis was conducted with a characterization factor of 0.5, associated with a biomass rotation period of about 48 years, where the forest is re-established to its original state within this period. By decreasing the characterization factor to 0.5, the GWP contribution of RWB combustion was reduced by 50%, reducing the total GWP of 1 tonne of packaged DPM by 24.1%.

To explore the sensitivity of the data required to estimate the electricity usage of the manure driers, an analysis was conducted that decreased the power rating settings from 100% capacity (2.2 kW) to 75% (1.6 kW), 50% (1.1 kW), and 25% (0.5 kW).

Ultimately, the variation in power ratings only slightly affected the GWP of the Manure Drying process, reducing it by 25% with each sensitivity analysis. The baseline results showed that manure drying contributed to 30% of the total GWP; through the sensitivity analyses, there was only a maximum 2% decrease from the baseline results.

Within both LCAs, sensitivity analyses were applied to various input parameters to test the robustness of the data used and to see how the change in the input parameter altered the baseline results. A sensitivity analysis was conducted on the 50/50 recycling approach as it was applied to the LCA of both companies and is a major methodological decision in estimating the upstream impacts associated with poultry manure. Both 0% and 100% of the impacts associated with inorganic N, P, and K fertilizers were used in the model. Accounting for 0 and 100% of the impacts associated with manufacturing fertilizer increased and decreased the total GWP of each system by 30-50%. It was concluded that the 50/50 recycling approach and the associated inputs are sensitive as the environmental impacts changed by over 15% compared to the baseline results.

4.4. Discussion

Dehydrated poultry manure is a recycled, value-added product that provides an organic fertilizer to producers. This study aimed to quantify the environmental impacts of the manufacturing of DPM pellets using poultry manure, identify hotspots of impacts, and determine ways to reduce the impacts. The results will be mainly discussed around GWP as AP, EP, and RE impacts are considered minor (Hasler et al., 2017; Kiss et al., 2021).

4.4.1. Environmental Impacts of Manure Sourcing

The manure-sourcing process was the largest contributor to all four environmental impact categories (GWP, AP, EP, and RE). Most of the impacts were associated with the upstream environmental burdens associated with the nutrients within the manure. The DPM product is primarily used as a soil amendment to supply N, P, and K. These nutrients originate from poultry feed grown with manufactured fertilizers. Inorganic N alone accounted for between 27% and 32% of the total impacts. In LCAs of crop and livestock production systems, the production of N fertilizers is a key driver of GHG emissions (Pelletier, 2017). This is because of the high energy demand associated with manufacturing inorganic N (i.e., ammonia (NH_3) synthesis) (Pelletier et al., 2008; Hoeppner et al., 2007; Pimentel et al., 2005). Given that the energy source (CH_4) for NH_3 synthesis is also fossil fuel-based, the production of inorganic N fertilizer is carbon-intensive (Walling et al., 2020; Basosi et al., 2014).

The impacts of other fertilizer inputs (inorganic P and K) contribute to the environmental impact categories, although to a lesser extent. Common conventional P_2O_5 products used in crop production, which include di-ammonium phosphate (DAP) and mono-ammonium phosphate (MAP), are manufactured using NH_3 and phosphoric acid (H_3PO_4) from the extraction of raw minerals such as rock phosphate (Zhang et al., 2017). In contrast, conventional K products are derived from K salts, which yield chloride (KCl) (e.g., muriate of potash (MOP)) and are manufactured through mining and extraction (Ushakova et al., 2023).

In this study, manure is considered a resource flow instead of a co-product or a waste product. If considered a co-product, the ISO LCA standards state that allocation should be avoided by dividing the product systems into unit processes and measuring the inputs and outputs related to each product (eggs or chickens) and the co-product (manure). This is usually not practical to do in most systems. But in this case, it can be argued that tracing the nutrients in the manure to the inorganic fertilizers used to grow crops to feed the poultry, in effect, is similar to dividing up the system into unit processes. Treating the nutrients in the manure as a recycling of a resource from poultry or egg production becomes a recycling problem and not a co-product problem. In classic recycling problems, the 50/50 recycling approach is applied to LCAs that account for upstream impacts of recycled materials, such as aluminum cans, in a secondary life cycle (Allacker et al., 2014).

The resource to be recycled (e.g., aluminum can be used to make another can) takes on 50% of the burden associated with extracting and processing virgin aluminum because recycling cannot exist without the original virgin material. In the manure, 50% of the impacts associated with the manufacture of inorganic fertilizer for the proportion of nutrients found in the manure was assigned to the DPM manufacturing process, and the other 50% would be assigned to the crop that would use the DPM. There are arguments that 100% of the impact should go to the one or the other system in a recycling scenario. However, the approach should reflect the physical and economic reality of the resource flow. Schrijvers et al. (2015) argue that the approach to dealing with recycling resources requires a case-by-case analysis.

It is important to note that there is a lot of disagreement and controversy in the LCA literature regarding how to, or whether to, account for upstream impacts associated with manure. This is partly due to a lack of understanding of the ISO guidelines and different manure management contexts. There are three common approaches to dealing with manure:

I. Manure is treated as a waste; therefore, no environmental impact is associated with it (Kiss et al., 2021; Bora et al., 2020; Sarlaki et al., 2021). However, this is not an acceptable approach within LCA guidelines. There is broad agreement that co-products (or resource flows) cannot be burden-free (Dominguez Aldama et al., 2023; Leip et al., 2019; Olofsson & Borjesson, 2018; Pelletier et al., 2015; Allacker et al., 2014).

II. Provide credit to the crop system since it is assumed that using manure instead of fertilizer offsets the impacts of fertilizer production (Corbala-Robles et al., 2018; Williams et al., 2016; Beausang et al., 2020). This approach is an 'avoided burdens' approach associated with the co-product treatment approach known as 'system expansion' (ISO 14044, 2006) and should only be used in consequential LCAs, as there is no guarantee that fertilizer production is reduced, particularly if the use of manure is already a common practice.

III. Allocate the impacts between the main product (eggs or poultry) and manure using biophysical or economic allocation. Biophysical allocation is often used to assign impacts between multiple products in livestock systems (e.g., Chen et al., 2017; Pelletier et al., 2015). Assigning an environmental burden to manure on a physical or economic basis ensures accountability within the agricultural industry and assists in accounting for the impacts of recycled resources used within the CE.

Regardless of which approach is used to deal with environmental burdens associated with manure production, a sensitivity analysis of the method is required, especially when comparing systems to ensure that results are consistent (i.e., product A always has a lower impact than product B, regardless of the method used. In other words, the relative impacts are consistent even if the absolute values change). In a study of poultry co-products, including fat, by-product meal, and hydrolyzed feather meal, Campos et al. (2019) conducted sensitivity analyses on different allocation methods to account for the co-products of poultry production (e.g., fat, by-product meal, and hydrolyzed feather meal). They found that using mass allocation leads to a 9-25 times higher impact on manure than using economic allocation. This is because manure has a high volume and mass but a very low market value.

Ultimately, the selected multifunctional solutions used in LCA studies must be clear, transparent, justifiable, and motivated in relation to the goals and scope of the studied system (Pelletier et al., 2015). However, they should also be based on the regulatory, physical, and economic contexts in which the products exist. More recently, there have been attempts to deal with how to assign impacts to manure based on specific contexts. For example, Leip et al. (2019) describe “a not so far-fetched hypothetical scenario” that is, if a farmer was required to adhere to a regulated emissions cap, their purchasing decisions for nutrient amendments may be based on not only the nutrient content and price of fertilizer or manure but the embodied GHG emissions as well. Leip et al. (2019) consider both a theoretical and a pragmatic approach based on nutrient cost and farmers' nutrient requirements. These approaches set out to create awareness that when using manure for its nutrient value for crop production in its continued life cycle, some of the environmental burdens associated with its use (upstream impacts) should be positioned in the crop production system. It is emphasized that regardless of how manure is treated in a life cycle assessment (i.e., treated as a co-product), providing an environmental burden to its use provides an economic and sustainability incentive for progressive manure management (Leip et al., 2019).

4.4.2. Impacts from Energy Required for Manure Drying

Based on the LCA results, the average impacts of the two manure drying processes contributed to 30% of the total GWP (89.6 kg CO_2 eq per tonne of DPM) and is considered an environmental hotspot in the manufacturing of DPM. In this study, the impacts associated with manure drying can be attributed to the upstream impacts of both electricity and the estimated impacts associated with the sourcing of biofuel, as well as the estimated emissions associated with the combustion of biofuel. However, other DPM products may use other energy sources for drying, including fossil fuels.

As manure MC is variable and various heat sources are used in drying (e.g., electricity, natural gas, biofuel, biogas), estimating the energy consumption of manure drying appears to be very scenario-dependent. In an LCA of pelletized compost, the energy required for the drying process was estimated to contribute 72.74 kg CO_2-eq to GWP per 1 ton (0.9 tonnes) of agro-biowaste compost (Sarlaki et al., 2021). In a comparative LCA which assessed the environmental impacts of different inorganic fertilizer products in comparison with composted pelletized poultry litter (CPPL) production, it was determined that the production of 1 kg of CPPL contributed 0.273 kg

(273 kg per tonne) of CO_2-eq to GWP. The MC of the feedstock decreased during the composting process to 22-28% MC and then further dried to 10-11% MC, but only stated that the CPPL was dried and did not specifically assess the environmental impacts associated with the drying technique.

In the case of manufacturing DPM in Eastern Canada, the two companies analyzed used very different drying systems with different energy sources. In addition, the raw manure characteristics, especially the MC, were very different for each system. The energy required to dry the manure specific to each drying system was unavailable from the companies. Both systems required a separate set of assumptions to estimate their energy use. Ideally, obtaining the specific energy consumption of each drying system would have allowed for increased confidence in this analysis.

4.4.3. Factors in Estimating the Environmental Impacts of Drying Manure

4.4.3.1. Factors Estimating the Environmental Impacts Associated with Drying Broiler Manure

The two operations had distinct drying systems in this LCA, and each required several assumptions to effectively account for the energy use, potential emissions, and upstream impacts of energy sourcing associated with the specific system. In the broiler-based poultry DPM production system, RWB was used as a biofuel which underwent complete combustion in a suspension burner and produced heat for drying the poultry manure. In addition to estimating the CO_2 produced from the combustion of the RWB, it was also important to consider the impact of transporting the RWB and the upstream impacts associated with forestry activities that sourced the biomass for chipboard manufacturing.

In LCA research, the CO_2 emissions from biomass combustion, such as forest products, are often considered C neutral (Cherubini et al., 2011). This approach is motivated by the belief in C neutrality of bioenergy due to the assumption that the CO_2 released from the harvesting and combustion of biofuel is equal to the amount of C that will be sequestered from the successive growing biomass. However, the C neutrality of bioenergy assumes fast regrowth of forested biomass. Cherubini et al. (2011) have identified that bioenergy can increase GWP even if it is regarded as carbon neutral in the long term. This is because the CO_2 emission from the initial burning of biomass is immediately released into the atmosphere and has immediate global warming impacts. However, the forest regrowth and re-sequestration of CO_2 may take decades to centuries, depending on whether the land is returned to forest, the forestry management practices, forest regrowth rate, climate, tree species, etc. (Cherubini et al., 2011). Thus, global warming impacts are even from bioenergy sources, such as using RWB in the manure drying process.

To appropriately characterize the CO_2 emissions of the combustion of RWB, the analysis would require specific information surrounding the forest management practices of the sourced wood and the alternate uses of the RWB if it was not used in this system. As details about the forest management are unavailable, this leads to uncertainty in estimating the impact of RWB as an energy source. An additional characterization factor was included in the environmental impact method to represent the environmental impacts of the CO_2 emissions on GWP associated with using RWB (TRACI v2.1.). An elemental output flow was added to the model and labelled as "Forest_ CO_2" to represent the CO_2 emissions to GWP from the combustion of RWB. In the model, the emissions are characterized by 1.0 kg of CO_2-eq/tonne of DPM, which represents 100% of the CO_2 emissions associated with combustion, are being emitted to the atmosphere and contributing to GWP. This characterization factor of 1.0 kg of CO_2-eq/tonne of DPM is a conservative representation. According to (Cherubini et al., 2011), the GWP for regenerated biomass systems for a 100-year time horizon ranges from 0.01 to 1.05 for 1 and 100 years biomass rotations, respectively. It characterizes the worst-case scenario of forestry management practices (i.e., a forested system that is not sustainably managed and, therefore, not sequestering biogenic C).

The practical benefits of using the suspension burner with RWB as a biofuel should be considered. In the case of the suspension burner system, it appears that this is an upgraded system and more environmentally sound heating method than the previously owned system based on external consultation. The environmental trade-off of using RWB as a biofuel is unknown as there was little information about the alternative end-of-life scenario for RWB.

4.4.3.2 Factors Estimating the Environmental Impacts Associated with Drying Layer Manure

The DPM derived from layer hens used manure that was pre-dried at each barn from which manure was sourced. All layer barns have mechanical dryer system consisting of fans, conveyors, and augers operating with electricity. However, only the number of fans, the power rating, and run time were available. Additionally, the actual electricity consumption of the dryer unit could not be separated from the electrical use of the layer barn(s). As such, the power rating and number of fans were used to estimate the annual kWh on the dryer of one farm was estimated and used to calculate the total electricity used per tonne of semi-dried manure for the total volume of manure handled from all barns.

The input data for the driers was based solely on an estimate of electricity consumption by fans operating continuously at full capacity. To see if this was a reasonable estimate, this estimated electricity consumption for the drier was subtracted from the total electricity consumption of the whole facility (i.e., barn + drier) to see what the remaining barn consumption would be. The remaining barn electricity use was quite low when considering the range of electricity consumption in layer barns from other references (see Turner et al., 2022). Thus, the electricity use associated with the drier is suspected to overestimate actual use.

In terms of the layer barns, the use of drying equipment attached to barns to utilize heat that would otherwise be lost appears to be an efficient method to dry manure (Li et al., 2020). Literature has reported that the optimal combination to efficiently dry layer hen manure was the hot air temperature of 35°C, air velocity of 1.60 m/s, and manure layer thickness of 85 mm (Li et al., 2020). However, the drying characteristics associated with the manure driers were unavailable. Ideally, the actual power use of the drying system would be metered separately from the barn. Alternatively, the power ratings of all motors and their operational settings, including those for fans, conveyor belts, augers, and any other additional fans, could be used to provide a calculated estimate of power use. Regardless, as the electricity used in the manure drying systems is sourced from hydropower, the impacts associated with drying are relatively low compared to if the electricity was sourced from natural gas, coal or coke.

4.4.4. Energy Required for Manufacturing of DPM not Including Drying

The GWP results for the DPM manufacturing processes in this study are in a similar range as reported in the literature relating to pellet production that uses different feedstocks and volumes of feedstocks (Padilla-Rivera et al., 2017; Kylili et al., 2016). Kiss et al. (2021) accounted for electricity in the production of CPPL but did not differentiate its contribution to the environmental impact categories.

The location of the facilities will determine the electricity grid's primary energy sources and influence the environmental impact categories. This LCA encompassed two companies in separate provinces. One company uses Quebec Hydro which produces electricity from what is considered renewable sources. On the contrary, the other company uses New Brunswick Power, which produces its electricity from a mixture of renewable and non-renewable sources, such as the burning of coal, natural gas, and fossil fuels. Taking an average of the environmental impacts of the two manufacturing processes does not highlight the importance of this. The pelletizing and manufacturing process can have significant contributions to the total environmental impacts if the company is based in a province with a “dirty” power grid.

4.5. Limitations of Study and Recommendations

The purpose of this study was to quantify the environmental impacts associated with manufacturing DPM in Eastern Canada. As per the study's limitations, it is recommended that more rigorous data is collected on energy consumption, emissions measurements and upstream impacts associated with the energy sources used in the drying systems and the use of manure. There were major data gaps associated with key drivers of impacts, including:

I. *Two unique operations were used to estimate the impacts of manufacturing DPM*: Evaluating the impacts of two highly unique operations poses limitations because the two systems are potentially not comparable, and it may be argued that averaging two different systems may not fully represent the environmental impacts associated with manufacturing DPM. In this analysis, two separate LCAs were conducted on two very different DPM manufacturing companies that utilized manure from different sources (i.e., broiler vs layer), two unique heat sources for drying manure (i.e., heat from layer barn vs combustion of biofuel), two unique drying systems, two different electricity grids, and based on the companies GAs, the end DPM products are different as well. Ideally, two separate LCAs could highlight the environmental impacts associated with manufacturing. Regardless, the results are fascinating, as the total environmental impact associated with each individual company is very similar.

II. *Estimating the upstream impacts associated with RWB as a biofuel*: As mentioned, the details about the forest management are unavailable, leading to uncertainty in estimating the upstream impacts associated with the biogenic C in the use of RWB as a biofuel. The use of RWB contributes greatly to the impact categories (GWP, AP, EP, and RE). In this analysis, we used a worst-case scenario for Eastern Canada and a sensitivity analysis accounting for half of the biogenic C in the RWB. An understanding of the forest management practices such as regrowth and harvest timelines along with knowledge of alternative end-of-life scenarios for the RWB from the OSB production that could potentially produce more potent GHG emissions such as methane (i.e., landfilled, composted) may allow for more accurate characterization factor of the CO_2 emissions from the combustion in the modelling and could assist in accurately estimating the biomass rotation and reduce the overall GWP of DPM.

III. *Estimating the electricity usage of the manure dryer(s):* The electricity usage of the manure dryer(s) posed a wide range of data gaps. Only the number of fans, their power rating, the run time of the manure dryer, and the combined electricity usage of both the on-site barn and manure dryer were available. Comparing the electricity consumption of the layer barn from the manure dryer through literature posed challenges as the most recent Canadian literature on conventional layer production used a weighted average, which ranged from 6 to 1429 kWh per 1 tonne of eggs (Turner et al., 2022). Ideally, the electricity usage of all the individual manure dryers from each of the partnering layer barns from which manure is sourced would be available (i.e., meter each manure dryer).

IV. *Estimating the environmental impacts on a per packaged unit basis:* The impacts estimated in this cradle-to-facility gate life cycle were calculated on an output basis per 1 tonne of packaged DPM. In reality, both companies produce more than one product, which may contain a different volume and packaging material (e.g., 1 tonne totes, 1 kg bag, 500-gram boxes), sometimes with different GAs. The inputs and outputs associated with manufacturing 1 tonne of DPM could not be separated on a per-packaged product basis due to data gaps and the inability to retrieve input data specific to each packaged unit. For example, both companies produced granules (i.e., crumbled pellets), but the electricity could not be isolated for the crumbling machine as there were no meters or ability to track motors on the crumbler. It is recommended that future analysis estimate the impacts on a per unit basis for each unique product as it would be valuable for the manufacturer to understand the impacts associated with each product.

V. *Estimating the upstream impacts associated with manure*: Based on the 50/50 recycling approach, manure usage is the highest contributing input to the selected environmental impact categories due to the upstream impacts associated with inorganic fertilizer production. This approach accounts for the impacts associated with manure usage but may not be the most representative method to account for the impacts. As this is a contentious subject in LCA, and there are many approaches, it is recommended that future analyses perform sensitivity analyses on different allocation methods (e.g., mass, biophysical) when estimating the impacts of manufacturing DPM and manure valorization. Completing this would require modelling the layer and broiler production systems.

VI. *Transportation of raw manure*: Transportation of raw manure to treatment facilities can be a bottleneck because of the high moisture content as raw manure is extremely heavy, and large volumes result in high costs that limit the feasibility of recycling manure (Foged et al., 2012). However, both companies have overcome common issues in sourcing manure (e.g., pre-drying manure or being in a centralized location). In the case of the laying hen system, most of the drying occurs onsite at each barn that partners with the company, reducing MC from 85 to 15-20%. Pre-drying the manure before transport makes it feasible to source manure from significant distances. Although not considered in this study, transporting fertilizer products across large distances could greatly increase the impacts. Regional production of DPM could have lower impacts than transporting them over large distances and should be considered in future studies.

VII. Although *packaging* contributed 5 to 8% of the impacts across the selected categories, GWP, AP, EP, and RE, this is an input that the companies might be able to choose to have lower impact (e.g., plastic or nylon material). Future studies should consider various packaging options.

VIII. *Following the impacts of DPM on the field*: Measuring or estimating the environmental impacts associated with the use of DPM in a field setting would allow manufacturers and users of the product to have a clear sense of the whole environmental performance of DPM. Additionally, having a complete picture of the alternative end-of-life scenarios for raw poultry manure (e.g., land application or landfill) in a particular region could provide a complete picture of the environmental trade-off of DPM.

This study is a valuable tool for scoping, organizing, and prioritizing issues and data collection and is the initial step to a more detailed assessment. Several data gaps and uncertainty in the data affect the final use of the results and provide opportunities for improved data collection for future analysis. Improved data collection could support more rigorous LCA results that could be used to make environmental claims about the product. Understanding these systems will assist in the company's decision-making regarding sustainable production practices and marketing. Lastly, we will gain an understanding of DPM's role in the CE.

4.6. Conclusion

The study's goals were to quantify the life cycle impacts of manufacturing DPM within Eastern Canada to help determine if there can be an opportunity to reduce emissions associated with the product's manufacturing and to understand the hotspots within the product system. This is the first study to quantify the life cycle impacts of manufacturing DPM within Canada and allows manufacturers to have insight into the hotspots associated with the production of DPM as a value-added nutrient product. The environmental burdens associated with manure as a resource input (Manure sourcing) contributed the most to the assessed environmental impact categories, mostly due to the N fertilizer and P and K manufacturing. Manure drying was the second largest contributor to the environmental impact categories assessed due to energy consumption, followed by DPM manufacturing. Dehydrated poultry manure as a fertilizer product is an example of a desirable organic fertilizer that may fit within the circular economy, as it has the opportunity to recycle a waste by-product while creating economic activity and providing a service to organic producers. This research identified challenges and constraints related to estimating the impacts of DPM manufacturing, informed industry partners about hotspots in their manufacturing process, and provided new information for agricultural sector leaders and policymakers on how valorization of recycled agricultural materials may be assessed.

References

Alam, M. Z., Lynch, D. H., Tremblay, G., Gillis-Madden, R., & Vanasse, A., 2018. Optimizing combining green manures and pelletized manure for organic spring wheat production. Canadian Journal of Soil Science, 98(4), 638–649. https://doi.org/10.1139/CJSS-2018-0049.

Allacker, K., Mathieux, F., Pennington, D., & Pant, R., 2014. The search for an appropriate end-of-life formula for the purpose of the European Commission Environmental Footprint initiative. Journal of Cleaner Production, 22(9), 1441–1458. https://doi.org/10.1007/s11367-016-1244-0.

Akerman, M., Humalisto, N., & Pitzen, S., 2020. Material politics in the circular economy: The complicated journey from manure surplus to resource. Geoforum, 116, 73-80. http://doi.org/10.1016/j.geoforum.2020.07.013.

van Asselt, E. D., van Bussel, L. G. J., van Horne, P., van der Voet, H., van der Heijden, G. W. A. M., & van der Fels-Klerx, H. J., 2015. Assessing the sustainability of egg production systems in The Netherlands. Poultry Science, 94(8), 1742–1750. https://doi.org/10.3382/ps/pev165.

Babaee A, Shayegan J, & Roshani A. Anaerobic slurry co-digestion of poultry manure and straw: effect of organic loading and temperature. Journal of Environmental Health Sci Eng, 11(1), 15. https://doi.org/10.1186/2052-336X-11-15.

Basosi, R., Fierro, A., & Jez, S., 2014. Mineral Nitrogen Fertilizers: Environmental Impact of Production and Use Computational Chemistry View project Oxidative Enzymes View project. https://www.researchgate.net/publication/264124538.

Beausang, C., Mcdonnell, K., & Murphy, F., 2020. Anaerobic digestion of poultry litter- A consequential life cycle assessment. Science of the Total Environment, 735, 139494. https://doi.org/10.1016/j.scitotenv.2020.139494.

Boggia, A., Paolotti, L., & Castellini, C., 2010. Environmental impact evaluation of conventional, organic and organic-plus poultry production systems using life cycle assessment. World's Poultry Science Journal, 66(1), 95–114. https://doi.org/10.1017/S0043933910000103.

Bolan, N. S., Szogi, A. A., Chuasavathi, T., Seshadri, B., Rothrock, M. J., & Panneerselvam, P., 2010. Uses and management of poultry litter. World's Poultry Science Journal, 66(4), 673–698. https://doi.org/10.1017/S0043933910000656.

Bora, R. R., Lei, M., Tester, J. W., Lehmann, J., & You, F., 2020. Life cycle assessment and techno-economic analysis of thermochemical conversion technologies applied to poultry litter with energy and nutrient recovery. ACS Sustainable Chemistry and Engineering, 8(22), 8436–8447. https://doi.org/10.1021/acssuschemeng.0c02860.

Brunerová, A., Müller, M., Gürdil, G. A. K., Šleger, V., & Brožek, M., 2020. Analysis of the physical-mechanical properties of a pelleted chicken litter organic fertilizer. Research in Agricultural Engineering, 66(4), 131–139. https://doi.org/10.17221/41/2020-RAE.

Bryant, R. B., Endale, D. M., Spiegal, S. A., Flynn, K. C., Meinen, R. J., Cavigelli, M. A., & Kleinman, P. J., 2022. Poultry manureshed management: Opportunities and challenges for a vertically integrated industry. Journal of Environmental Quality, 51(4), 540–551. https://doi.org/10.1002/jeq2.20273

Campos, I., Valente, L. M. P., Matos, E., Marques, P., & Freire, F., 2020. Life-cycle assessment of animal feed ingredients: Poultry fat, poultry by-product meal and hydrolyzed feather meal. 252, 119845. https://doi.org/10.1016/j.jclepro.2019.119845.

Chadwick, D., Wei, J., Yan, T., Guanghui, Y., Qirong, S., & Qing, C., 2015. Improving manure nutrient management towards sustainable agricultural intensification in China. Agriculture, Ecosystems & Environment, 209, 34-46. https://doi.org/10.1016/j.agee.2015.03.025.

Chen, X., Wilfart, A., Puillet, L., & Aubin, J., 2017. A new method of biophysical allocation in LCA of livestock co-products: modelling metabolic energy requirements of body-tissue growth. International Journal of Life Cycle Assessment, 22(6), 883–895. https://doi.org/10.1007/s11367-016-1201-y.

Cheng, M., Mccarl, B., & Fei, C., 2022. Climate change and livestock production: A literature review. Atmosphere, 13, 140. 10.3390/atmos13010140.

Cherubini, F., Peters, G. P., Berntsen, T., Strømman, A. H., & Hertwich, E., 2011. CO_2 emissions from biomass combustion for bioenergy: Atmospheric decay and contribution to global warming. GCB Bioenergy, 3(5), 413–426.https://doi.org/10.1111/j.1757-1707.2011.01102.x.

Chicken Farmers of Canada., 2019. Chicken Farmers of Canada Annual Report. https://www.chickenfarmers.ca/wp-content/uploads/2020/03/Annual-report-2019-–-E-Web.pdf (accessed March 21st, 2022).

Corbala-Robles, L., Sastafiana, W. N. D., van Linden, V., Volcke, E. I. P., & Schaubroeck, T., 2017. Life cycle assessment of biological pig manure treatment versus direct land application − a trade-off story. Resource, Conservation and Recycling, 131, 86-98. https://doi.org/10.1016/j.resconrec.2017.12.010.

Costantini, M., Ferrante, V., Guarino, M., & Bacenetti, J., 2021. Environmental sustainability assessment of poultry productions through life cycle approaches A critical review. Trends in Food Science & Technology, 110, 201–212. https://doi.org/10.1016/j.tifs.2021.01.086.

Daniel, T. C., Sharpley, A. N., & Lemunyon, J. L., 1998. Agricultural phosphorus and eutrophication: A symposium overview. Journal of Environmental Quality, 27(2), 251–257. https://doi.org/10.2134/JEQ1998.00472425002700020002X.

Delgado, M., Rodríguez, C., Martín, J. V., Miralles De Imperial, R., & Alonso, F., 2011. Environmental assay on the effect of poultry manure application on soil organisms in agroecosystems, 461, 532-535 https://doi.org/10.1016/j.scitotenv.2011.11.047.

Dominguez Aldama, D., Grassauer, F., Zhu, Y., Ardestani-Jaafari, A., & Pelletier, N., 2023. Allocation methods in life cycle assessments (LCAs) of agri-food co-products and food waste valorization systems: Systematic review and recommendations. In Journal of Cleaner Production, 421, 138488. https://doi.org/10.1016/j.jclepro.2023.138488.

Dornelas, K. C., Schneider, R. M., & do Amaral, A. G., 2017. Biogas from poultry waste—production and energy potential. Environmental Monitoring and Assessment, 189(8), 1–11. https://doi.org/10.1007/s10661-017-6054-8

Duque-Acevedo, M., Belmonte-Ureña, L. J., Yakovleva, N., & Camacho-Ferre, F., 2020. Analysis of the circular economic production models and their approach in agriculture and agricultural waste biomass management. International Journal of Environmental Research and Public Health, 17(24), 9549. https://doi.org/10.3390/ijerph17249549

Ekvall, T., & Finnveden, G., 2001. Allocation in ISO 14041-a critical review. Journal of Cleaner Production, 9, 197–208. www.cleanerproduction.net.

Ellen MacArthur Foundation., 2013. Towards the circular economy Vol. 1: an economic and business rationale for an accelerated transition. Transitioning to a circular economy business | Report (ellenmacarthurfoundation.org). (Accessed January 12, 2024).

Ershadi, S. Z., Dias, G., Davoud Heidari, M., & Pelletier, N., 2020. Improving nitrogen use efficiency in crop-livestock systems: A review of mitigation technologies and management strategies, and their potential applicability for egg supply chains. Journal of Cleaner Production, 265, 121671. https://doi.org/10.1016/j.jclepro.2020.121671.

FAO, 2021. Agricultural Outlook 2021-2030. https://www.fao.org/3/cb5332en/Meat.pdf

FAO, 2018. Livestock and environment statistics: manure and greenhouse gas emissions. Global, regional and country trends 1990 – 2018. (http:/;www.fao.org/3/cb1922en/cb1922en.pdf).

FAO., 2011. World Livestock 2011 - Livestock in Food Security, Rome. World Livestock 2011 Livestock in food security (fsnnetwork.org).

Foged, H, L., Flotats, X., Blasi, A. B., Blasi., Palatsi, J., Magri, A., & Schelde., K. M., 2011. Inventory of manure processing activities in Europe. Technical Report No. I concerning “Manure Processing Activities in Europe” to the European Commission, Directorate-General Environment. 138 pp. Manure Processing Activities in Europe - Project reference: ENV.B.1/ETU/2010/0007 (upc.edu).

Flavel, T. C., & Murphy, D. V., 2006. Carbon and nitrogen mineralization rates after application of organic amendments to soil.

Fouli, Y., Hurlbert, M., & Kröbel, R., 2021. Greenhouse gas emissions from Canadian agriculture: Estimates and measurements. The Simpson Centre for Agriculture and Food Innovation and Public Education. University of Calgary, 14 (35). JSC5_GHG-Emissions_Fouli-et-al.pdf (policyschool.ca).

Gerber, P., Wassenaar, T., Rosales, M., Castel, V., Steinfeld, H., Bartley, M., Brugère, C., Soto, D., & Harvey, B., 2006. Environmental impacts of a changing livestock production: overview and discussion for a comparative assessment with other food production sectors. FAO/WFT Expert Workshop. 24-28 April 2006, Vancouver, Canada. FAO Fisheries Proceedings. No. 10. Rome, FAO. 2007. pp. 37–54.

Gerber, P. J., 2013. Tackling climate change through livestock: Global assessment of emissions and mitigation opportunities. Rome: Food and Agriculture Organization of the United Nations. https://www.fao.org/3/a-i3437e.pdf.

Goglio, P., Smith, W. N., Grant, B. B., Desjardins, R. L., Gao, X., Hanis, K., Tenuta, M., Campbell, C. A., McConkey, B. G., Nemecek, T., Burgess, P. J., & Williams, A. G., 2018. A comparison of methods to quantify greenhouse gas emissions of cropping systems in LCA. Journal of Cleaner Production, 172, 4010–4017. https://doi.org/10.1016/J.JCLEPRO.2017.03.133.

Government of Canada. 2023. Greenhouse gas emissions and agriculture. https://agriculture.canada.ca/en/environment/greenhouse-gases. (accessed March 20th, 2024).

Government of Canada. 2021. Canada’s chicken industry at a glance. https://agriculture.canada.ca/en/sector/animal-industry/poultry-egg-market-information/chicken (accessed March 21st, 2023).

Government of Nova Scotia., 2006. Manure Management Guidelines. https://novascotia.ca/thinkfarm/documents/manureguide_2006lowres.pdf (accessed March 23rd, 2023).

Gržinić, G., Piotrowicz-Cieślak, A., Klimkowicz-Pawlas, A., Górny, R. L., Ławniczek-Wałczyk, A., Piechowicz, L., Olkowska, E., Potrykus, M., Tankiewicz, M., Krupka, M., Siebielec, G., & Wolska, L., 2023. Intensive poultry farming: A review of the impact on the environment and human health. In Science of the Total Environment, 858, 160014. https://doi.org/10.1016/j.scitotenv.2022.160014.

Hanserud, O. S., Cherubini, F., Øgaard, A. F., Müller, D. B., & Brattebø, H., 2018. Choice of mineral fertilizer substitution principle strongly influences LCA environmental benefits of nutrient cycling in the agri-food system. Science of The Total Environment, 615, 219–227. https://doi.org/10.1016/J.SCITOTENV.2017.09.215.

Hasler, K., Bröring, S., Omta, S. W. F., & Olfs, H. W., 2015. Life cycle assessment (LCA) of different fertilizer product types. European Journal of Agronomy, 69, 41–51. https://doi.org/10.1016/J.EJA.2015.06.001.

Heijungs, R., & Kleijn, R., 2001. LCA Methodology - Numerical Approaches Towards Life Cycle Interpretation Five Examples. https://doi.org/10.1007/BF02978732.

Hijazi, O., Munro, S., Zerhusen, B., & Effenberger, M., 2016. Review of life cycle assessment for biogas production in Europe. Renewable and Sustainable Energy Reviews, 54, 1291-1300. https://doi.org/10.1016/j.rser.2015.10.013.

Hidalgo, D., & Corona, F., 2023. Livestock manure valorization to biochemical's and energy. In: Jawaid, M., Khan, A. (eds) Manure Technology and Sustainable Development. Sustainable Materials and Technology. Springer, Singapore. https://doi.org/10.1007/978-981-19-4120-7_9.

Hoeppner, J. W., Entz, M. H., Mcconkey, B. G., Zentner, R. P., & Nagy, C. N., 2021. Energy use and efficiency in two Canadian organic and conventional crop production systems. https://doi.org/10.1079/RAF2005118.

Hofmann, N., & Beaulieu, M. S., 2001. A geographical profile of manure production in Canada, 2001. Statistics Canada Agriculture Division. A geographical profile of manure production in Canada, Agriculture and Rural Working Paper Series.

Hollas, C. E., Rodrigues, H. C., Oyadomari, V. M. A., Bolsan, A. C., Venturin, B., Bonassa, G., . . . Kunz, A., 2022. The potential of animal manure management pathways toward a circular economy: A bibliometric analysis. Environmental Science and Pollution Research, 29(49), 73599-73621. https://doi.org/10.1007/s11356-022-22799-y.

Ilea, R. C., 2009. Intensive livestock farming: Global trends, increased environmental 22(2), 153–167. https://doi.org/10.1007/S10806-008-9136-3.

IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Available online: https://www.ipcc.ch/report/ar6/wg3/ (Accessed March 20th, 2023).

ISO, 2006. Environmental Management - Life Cycle Assessment - Principals and Framework. International Organizations for Standardization, ISO14040-14044.

Kabongo, Jean D., 2013. Waste Valorization. In: Idowu S.O., Capaldi N., Zu L., & Gupta A.D. In eds. Samuel O Idowu, Nicholas Capaldi, Liangrong Zu, and Ananda Das Gupta. Berlin, Heidelberg: Springer Berlin Heidelberg, 2701–6. https://doi.org/10.1007/978-3-642-28036-8_680.

Kanani, F., Davoud Heidari, M., Gilroyed, B. H., Pelletier, N., & Zhifu, M., 2020. Waste valorization technology options for the egg and broiler industries: A review and recommendations Handling editor. https://doi.org/10.1016/j.jclepro.2020.121129.

Kapoor R, Ghosh P, Kumar M, Sengupta S, Gupta A, Kumar SS, Vijay V, Kumar V, Kumar Vijay V, Pant D., 2020. Valorization of agricultural waste for biogas based circular economy in India: a research outlook. Bioresource Technology, 304:123036. https://doi. org/10.1016/j.biortech.2020.123036.

Karki R, Chuenchart W, Surendra KC, Shrestha S, Raskin L, Sung S, Hashimoto A, Kumar Khanal S., 2021. Anaerobic co-digestion: Current status and perspectives. Bioresource Technology, 330(21), 125001. https://doi:10.1016/j.biortech.2021.125001.

Kingery, W. L., Wood, C.W., Delaney, D. P., Williams, J. C., Mullins, G.L. & van Santen, E., 1993, Implications of long-term land application of poultry litter on tall fescue pastures. Journal of Production Agriculture, 6: 390-395. https://doi.org/10.2134/jpa1993.0390.

Kiss, N. É., Tamás, J., Szőllősi, N., Gorliczay, E., & Nagy, A., 2021. Assessment of composted pelletized poultry litter as an alternative to chemical fertilizers based on the environmental impact of their production. Agriculture (Switzerland), 11, 1130. https://doi.org/10.3390/agriculture11111130.

Kumar, R., Ju Park, B., Young Cho, J., Kumar, R. R., Park contributed equally R R Kumar, B. J., Cho, J. Y., & Park, B. J., 2013. Application and environmental risks of livestock manure. J Korean Soc Appl Biol Chem, 56, 497-503. https://doi.org/10.1007/s13765-013-3184-8.

Kylili, A., Christoforou, E., & Fokaides, P. A., 2016. Environmental evaluation of biomass pelleting using life cycle assessment. Biomass and Bioenergy, 84, 107–117. https://doi.org/10.1016/J.BIOMBIOE.2015.11.018.

Leinonen, I., & Kyriazakis, I., 2016. How can we improve the environmental sustainability of poultry production? Proceedings of the Nutrition Society, 75(3), 265–273. https://doi.org/10.1017/S0029665116000094.

Leip, A., Ledgard, S., Uwizeye, A., Palhares, J. C. P., Aller, M. F., Amon, B., Binder, M., Cordovil, C. M. d. S., de Camillis, C., Dong, H., Fusi, A., Helin, J., Hörtenhuber, S., Hristov, A. N., Koelsch, R., Liu, C., Masso, C., Nkongolo, N. v., Patra, A. K., … Wang, Y., 2019. The value of manure - Manure as co-product in life cycle assessment. Journal of Environmental Management, 241, 293–304. https://doi.org/10.1016/J.JENVMAN.2019.03.059.

Li, X., Zheng, W., Li, B., & Tong, Q., 2020. Optimization of low-temperature drying of laying-hen manure using response surface methodology. Journal of the Air and Waste Management Association, 70(2), 206–218. https://doi.org/10.1080/10962247.2019.1694092.

Liu, X., Elgowainy, A., & Wang, M., 2020. Life cycle energy use and greenhouse gas emissions of ammonia production from renewable resources and industrial by-products. Green Chem, 22, 5751. http://doi.org/10.1039/d0gc02301a

Ló Pez-Mosquera, M. E., Cabaleiro, F., Sainz, M. J., Ló Pez-Fabal, A., & Carral, E., 2007. Fertilizing value of broiler litter: Effects of drying and pelletizing. https://doi.org/10.1016/j.biortech.2007.10.034.

Lu, C., & Tian, H., 2017. Global nitrogen and phosphorus fertilizer use for agriculture production in the past half century: Shifted hot spots and nutrient imbalance. Earth System Science Data, 9(1), 181–192. https://doi.org/10.5194/essd-9-181-2017.

Lynch, D. H., Zheng, Z., Zebarth, B. J., & Martin, R. C., 2008. Organic amendment effects on tuber yield, plant N uptake and soil mineral N under organic potato production. Renewable Agriculture and Food Systems, 23(3), 250–259. https://doi.org/10.1017/S1742170508002330.

Mackenzie, S. G., Leinonen, I., & Kyriazakis, I., 2017. The need for co-product allocation in the life cycle assessment of agricultural systems—is “biophysical” allocation progress? International Journal of Life Cycle Assessment, 22(2), 128–137. https://doi.org/10.1007/s11367-016-1161-2.

Mainali, B., Emran, S. B., & Silveira, S., 2017. Greenhouse gas mitigation using poultry litter management techniques in Bangladesh. Energy, 127, 155–166. https://doi.org/10.1016/J.ENERGY.2017.03.103.

Matthews, S., Hendrickson, Chris. T., & Matthews, Deanna. H., 2014. Life cycle assessment - quantitative approaches for decisions that matter. http://www.lcatextbook.com/.

McClelland, S. C., Arndt, C., Gordon, D. R., & Thoma, G., 2018. Type and number of environmental impact categories used in livestock life cycle assessment: A systematic review. In Livestock Science, 209, 39–45. https://doi.org/10.1016/j.livsci.2018.01.008.

Menegat, S., Ledo, A., & Tirado, R., 2022. Greenhouse gas emissions from global production and use of nitrogen synthetic fertilisers in agriculture. Scientific Reports, 12(1), 14490. https://doi.org/10.1038/s41598-022-18773-w.

Michiels, F., Hubo, L., & Geeraerd, A., 2021. Why mass allocation with representative allocation factor is preferential in LCA when using residual livestock products as organic fertilizers. Journal of Environmental Management, 297, 113337. https://doi.org/10.1016/j.jenvman.2021.113337.

Moore, P., Daniel, T., Sharpley, A., Wood, C., Daniel, C., & Wood, C. W., 1995. Poultry manure management: Environmentally sound options. Journal of Soil and Water Conservation, 50(3).

Mottet, A., & Tempio, G., 2017. Global poultry production: Current state and future outlook and challenges. In World’s Poultry Science Journal, 73(2), 245–256. Cambridge University Press. https://doi.org/10.1017/S0043933917000071.

OECD-FAO., 2021. Agricultural Outlook 2021-2030. OECD Agriculture statistics (database).

Olofsson, J., & Börjesson, P., 2018. Residual biomass as resource – Life-cycle environmental impact of wastes in circular resource systems. Journal of Cleaner Production, 196, 997-1006. https://doi.org/10.1016/j.jclepro.2018.06.115.

Padilla-Rivera, A., Barrette, J., Blanchet, P., & Thiffault, E., 2017. Environmental performance of eastern Canadian wood pellets as measured through life cycle assessment. Forests, 8(9), 352. https://doi.org/10.3390/f8090352.

Pelletier, N., 2008. Environmental performance in the US broiler poultry sector: Life cycle energy use and greenhouse gas, ozone depleting, acidifying and eutrophying emissions. Agricultural Systems, 98(2), 67-73. https://doi.org/10.1016/j.agsy.2008.03.007.

Pelletier, N., Doyon, M., Muirhead, B., Widowski, T., Nurse-Gupta, J., & Hunniford, M., 2018. Sustainability in the Canadian egg industry - Learning from the past, navigating the present, planning for the future. Sustainability (Basel, Switzerland), 10(10), 3524-. https://doi.org/10.3390/SU10103524.

Pelletier, N., 2017. Life cycle assessment of Canadian egg products, with differentiation by hen housing system type. Journal of Cleaner Production, 152, 167–180. https://doi.org/10.1016/J.JCLEPRO.2017.03.050.

Pelletier, N., Ardente, F., Brandão, M., de Camillis, C., & Pennington, D., 2015. Rationales for and limitations of preferred solutions for multifunctionality problems in LCA: is increased consistency possible? International Journal of Life Cycle Assessment, 20(1), 74–86. https://doi.org/10.1007/s11367-014-0812-4.

Pelletier, N., Ibarburu, M., & Xin, H., 2014. Comparison of the environmental footprint of the egg industry in the United States in 1960 and 2010. Poultry Science, 93(2), 241–255. https://doi.org/10.3382/ps.2013-03390.

Pelletier, N., & Tyedmers, P., 2011. An ecological economic critique of the use of market information in life cycle assessment research. Journal of Industrial Ecology, 15(3), 342–354. https://doi.org/10.1111/j.1530-9290.2011.00337.x.

Pennington, D. W., Potting, J., Finnveden, G., Lindeijer, E., Jolliet, O., Rydberg, T., & Rebitzer, G., 2004. Life cycle assessment Part 2: Current impact assessment practice. In Environment International, 30(5), 721–739. https://doi.org/10.1016/j.envint.2003.12.009.

Petersen, S. O., Blanchard, M., Chadwick, D., del Prado, A., Edouard, N., Mosquera, J., & Sommer, S. G., 2013. Manure management for greenhouse gas mitigation. Animal, 7(2), 266–282. https://doi.org/10.1017/S1751731113000736.

Petersen, S. O., Sommer, S. G., Béline, F., Burton, C., Dach, J., Dourmad, J. Y., Leip, A., Misselbrook, T., Nicholson, F., Poulsen, H. D., Provolo, G., Sørensen, P., Vinnerås, B., Weiske, A., Bernal, M. P., Böhm, R., Juhász, C., & Mihelic, R., 2007. Recycling of livestock manure in a whole-farm perspective. Livestock Science, 112(3), 180–191. https://doi.org/10.1016/j.livsci.2007.09.001.

Pimentel, D., Hepperly, P., Hanson, J., Douds, D., & Seidel, R., 2005. Environmental, energetic, and economic comparisons of organic and conventional farming systems. American Institute of Biological Sciences, 55(7), 573–582. https://doi.org/10.1641/0006-3568(2005)055[0573:EEAECO]2.0.CO;2.

Poore, J., & Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science, 360(6392), 987–992. https://doi.org/10.1126/SCIENCE.AAQ0216.

Potter, P., Ramankutty, N., Bennett, E. M., & Donner, S. D., 2010. Characterizing the spatial patterns of global fertilizer application and manure production. Earth Interactions, 14(2), 1-22. https://doi.org/10.1175/2009EI288.1.

Putman, B., Thoma, G., Burek, J., Matlock, M., & Martin, R. E., 2017. A retrospective analysis of the United States poultry industry: 1965 compared with 2010. Agricultural Systems, 157, 107-117. https://doi.org/10.1016/j.agsy.2017.07.008.

Qualman. D., & National Farmers Union. Agricultural greenhouse gas emissions in Canada: A new, comprehensive assessment. Saskatoon: NFU, 2022.

Rahman, S. H., Xin, S. A., Roberts, J. A., Arthur, R. T., Burns, H., Li, Z., Zhu, L. B., Moody, K. B., 2012. Effects of laying-hen strain on manure properties and ammonia emissions, Transactions of the ASABE, 55(3), 1059-1065. http://doi: 10.13031/2013.41510.

Ramankutty, N., Mehrabi, Z., Waha, K., Jarvis, L., Kremen, C., Herrero, M., & Rieseberg, L. H., 2018. Trends in global agricultural and use: Implications for environmental health and food security. Annual Review of Plant Biology, 69(1). https://doi.org/10.1146/annurev-arplant-042817-040256.

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W. P., Suh, S., Weidema, B. P., & Pennington, D. W., 2004. Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications. Environment International, 30(5), 701–720. https://doi.org/10.1016/J.ENVINT.2003.11.005.

Rees, H. W., Chow, T. L., Zebarth, B. J., Xing, Z., Toner, P., Lavoie, J., & Daigle, J. L., 2011. Effects of supplemental poultry manure applications on soil erosion and runoff water quality from a loam soil under potato production in northwestern New Brunswick. Canadian Journal of Soil Science, 91(4), 595–613. https://doi.org/10.4141/CJSS10093/ASSET/IMAGES/LARGE/CJSS10093F1.JPEG.

Ronga, D., Mantovi, P., Pacchioli, M. T., Pulvirenti, A., Bigi, F., Allesina, G., Pedrazzi, S., Tava, A., & Dal Prà, A., 2020. Combined effects of dewatering, composting and pelleting to valorize and delocalize livestock manure, improving agricultural sustainability. Agronomy, 10(5). https://doi.org/10.3390/AGRONOMY10050661.

Rosa, E., Arriaga, H., & Merino, P., 2022. Strategies to mitigate ammonia and nitrous oxide losses across the manure management chain for intensive laying hen farms. Science of The Total Environment, 803,150017. https://doi.org/10.1016/J.SCITOTENV.2021.150017.

Rosemarin, A., Ekane, N., & Andersson, K., 2021. Phosphorus flows, surpluses, and N/P agronomic balancing when using manure from pig and poultry farms. Agronomy, 11(11). https://doi.org/10.3390/AGRONOMY11112228.

Rubežius, M., Venslauskas, K., Navickas, K., & Bleizgys, R., 2020. Influence of aerobic pretreatment of poultry manure on the biogas production process. Processes, 8(9), 1109. https://doi.org/10.3390/pr8091109.

Sahin, O., Taskin, M. B., Kadioglu, Y. K., Inal, A., Pilbeam, D. J., & Gunes, A., 2014. Elemental composition of pepper plants fertilized with pelletized poultry manure, 37(3), 458–468. https://doi.org/10.1080/01904167.2013.864307.

Sarlaki, E., Kermani, A. M., Hossein., Kianmehr, M., Vakilian, K. A., Hosseinzadeh-Bandbafha, H., Ma, L., Aghbashlo, M., Tabatabaei, M., & Lam, S. S., 2021. Improving sustainability and mitigating environmental impacts of agro-biowaste compost fertilizer by pelletizing-drying. Environmental Pollution, 285, 117412. https://doi.org/10.1016/j.envpol.2021.117412.

Schrijvers, D. L., Loubet, P., & Sonnemann, G., 2016. A critical review of guidelines against a systematic framework with regard to consistency on allocation procedures for recycling in LCA. The International Journal of Life Cycle Assessment, 21, 994-1008. https://doi.org/10.1007/s11367-016-1069-x.

Schröder, J., 2005. Revisiting the agronomic benefits of manure: A correct assessment and exploitation of its fertilizer value spares the environment. Bioresource Technology, 96(2), 253–261. https://doi.org/10.1016/J.BIORTECH.2004.05.015.

Seidavi, A. R., Zaker-Esteghamati, H., & Scanes, C. G., 2019. Present and potential impacts of waste from poultry production on the environment. In World's Poultry Science Journal, 75(1), 29–42. Cambridge University Press. https://doi.org/10.1017/S0043933918000922.

Sieverding, H., Kebreab, E., Johnson, J. M. F., Xu, H., Wang, M., Grosso, S. J. D., Bruggeman, S., Stewart, C. E., Westhoff, S., Ristau, J., Kumar, S., & Stone, J. J., 2020. A life cycle analysis (LCA) primer for the agricultural community. Agronomy Journal, 112(5), 3788–3807. https://doi.org/10.1002/agj2.20279.

Shahbandeh., 2022, Poultry industry in Canada- statistics & facts, https://www.statista.com/topics/5441/poultry-industry-in-canada/#topicOverview (accessed March 21, 2023).

Sharara, M. A., Aguirre-Villegas, H. A., Larson, R. A., Sanford, J., Liu, Z., & Schott, L., 2021. Pelleting Animal Manures - Manure Processing Fact Sheet Series. https://content.ces.ncsu.edu/pelleting-animal-manures.

Sharifi, M., Lynch, D. H., Zebarth, B. J., Zheng, Z., & Martin, R. C., 2009. Evaluation of nitrogen supply rate measured by in situ placement of Plant Root Simulator™ probes as a predictor of nitrogen supply from soil and organic amendments in potato crop. American Journal of Potato Research, 86(5), 356–366. https://doi.org/10.1007/S12230-009-9090-2/FIGURES/4.

Statistics Canada., 2021. Canada's chicken industry at a glance, https://agriculture.canada.ca/en/sector/animal-industry/poultry-egg-market-information/chicken (accessed March 21st, 2022).

Sultana, A., Kumar, A., & Harfield, D., 2010. Development of agri-pellet production cost and optimum size. Bioresource Technology 101, 5609-5621. https://doi.org/10.1016/j.biortech.2010.02.011.

Turner, I., Heidari, D., & Pelletier, N., 2022. Life cycle assessment of contemporary Canadian egg production systems during the transition from conventional cage to alternative housing systems: Update and analysis of trends and conditions. Resources, Conservation and Recycling, 176, 105907. https://doi.org/10.1016/J.RESCONREC.2021.105907.

Thornton, P. K., 2010. Livestock production: recent trends, future prospects. Philosophical Transactions: Biological Sciences, 365(1554), 2853–2867. http://www.jstor.org/stable/20752983.

U.S. Department of Energy., n.d. Hydrogen Production: Biomass Gasification | Department of Energy (accessed February 3, 2024).

United Nations, The 2030 Agenda and the Sustainable Development Goals: An opportunity for Latin America and the Caribbean (LC/G.2681-P/Rev.3), Santiago, 2018. The 2030 Agenda and the Sustainable Development Goals: An opportunity for Latin America and the Caribbean (cepal.org) (accessed October 1, 2023).

Ushakova E, Perevoshchikova A, Menshikova E, Khayrulina E, Perevoshchikov R, Belkin P., 2023. Environmental aspects of potash Mining: A case study of the Verkhnekamskoe potash deposit. Mining, 3(2):176-204. https://doi.org/10.3390/mining3020011.

Vaarst, M., Steenfeldt, S., & Horsted, K., 2015. Sustainable development perspectives of poultry production. In World's Poultry Science Journal 71(4), 609–620. https://doi.org/10.1017/S0043933915002433.

Vergé, X. P. C., Dyer, J. A., Desjardins, R. L., & Worth, D., 2009. Long-term trends in greenhouse gas emissions from the Canadian poultry industry. Journal of Applied Poultry Research, 18(2), 210–222. https://doi.org/10.3382/japr.2008-00091.

Vergé, X. P. C., de Kimpe, C., & Desjardins, R. L., 2007. Agricultural production, greenhouse gas emissions and mitigation potential. Agricultural and Forest Meteorology, 142(2–4), 255–269. https://doi.org/10.1016/J.AGRFORMET.2006.06.011.

Vergé, X., Maxime, D., Desjardins, R. L., & Vanderzaag, A. C., 2015. Allocation factors and issues in agricultural carbon footprint: a case study of the Canadian pork industry. https://doi.org/10.1016/j.jclepro.2015.11.046.

de Vries, J. W., Groenestein, C. M., & de Boer, I. J. M., 2012. Environmental consequences of processing manure to produce mineral fertilizer and bio-energy. Journal of Environmental Management, 102, 173–183. https://doi.org/10.1016/J.JENVMAN.2012.02.032.

Walling, E., & Vaneeckhaute, C., 2020. Greenhouse gas emissions from inorganic and organic fertilizer production and use: A review of emission factors and their variability. In Journal of Environmental Management, 276. Academic Press. https://doi.org/10.1016/j.jenvman.2020.111211.

Wang, F., Pei, M., Qiu, L., Yao, Y., Zhang, C., & Qiang, H., 2019. Performance of anaerobic digestion of chicken manure under gradually elevated organic loading rates. International Journal of Environmental Research and Public Health, 16(12). https://doi.org/10.3390/IJERPH16122239.

Weidema, B., 2006. The product, functional unit and reference flow in LCA Introduction to the series: Vol. No. 70 (H. Wenzel, C. Petersen, & K. Hansen, Eds.). Danish Ministry of the Environment, Environmental Protection Agency.

Williams, A. G., Leinonen, I., & Kyriazakis, I., 2016. Environmental benefits of using turkey litter as a fuel instead of a fertilizer. Journal of Cleaner Production, 113, 167–175. https://doi.org/10.1016/J.JCLEPRO.2015.11.044.

Zhang, F., Wang, Q., Hong, J., Chen, W., Qi, C., & Ye, L., 2017. Life cycle assessment of diammonium- and monoammonium-phosphate fertilizer production in China. Journal of Cleaner Production, 141, 1087-1094. https://doi.org/10.1016/j.jclepro.2016.09.107.

Zhang, H., & Schroder, J. (eds.), 2014. Animal manure production and utilization in the US. Applied Manure and Nutrient Chemistry for Sustainable Agriculture and Environment, 1–21. https://doi.org/10.1007/978-94-017-8807-6_1.

Zhao, Y., Shepherd, T. A., Swanson, J. C., Mench, J. A., Karcher, D. M., & Xin, H., 2015. Comparative evaluation of three egg production systems: Housing characteristics and management practices. Poultry Science, 94(3), 475–484. https://doi.org/10.3382/ps/peu077.

Zhu, L., Lei, H., Zhang, Y., Zhang, X., Bu, Q., & Wei, Y., 2018. A review of biochar derived from pyrolysis and its application in biofuel production. SF Journal of Material and Chemical Engineering, 1(1).